# Fifth National Climate Assessment

U.S. Global Change Research Program

Full report available online at: nca2023.globalchange.gov

**Cover image**

Two volunteers help demonstrate and install solar panels in Highland Park, Michigan, in May 2021. The event was hosted by the local nonprofit Soulardarity, which teaches local residents about solar power, installs solar-powered streetlights that also provide wireless internet access, and helps local communities build a just and equitable energy system. Adopting energy storage with decentralized solutions, such as microgrids or off-grid systems, can promote energy equity in overburdened communities. Photo credit: Nick Hagen.

# Fifth National Climate Assessment

U.S. Global Change Research Program

The Fifth National Climate Assessment is the US Government's preeminent report on climate change impacts, risks, and responses. It is a congressionally mandated interagency effort that provides the scientific foundation to support informed decision-making across the United States.

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## Startlement

*by Ada Limón, 24th Poet Laureate Consultant in Poetry at the Library of Congress*

It is a forgotten pleasure, the pleasure
of the unexpected blue-bellied lizard

skittering off his sun spot rock, the flicker
of an unknown bird by the bus stop.

To think, perhaps, we are not distinguishable
and therefore no loneliness can exist here.

Species to species in the same blue air, smoke—
wing flutter buzzing, a car horn coming.

So many unknown languages, to think we have
only honored this strange human tongue.

If you sit by the riverside, you see a culmination
of all things upstream. We know now,

we were never at the circle's center, instead
all around us something is living or trying to live.

The world says, What we are becoming, we are
becoming together.

The world says, One type of dream has ended
and another has just begun.

The world says, Once we were separate,
and now we must move in unison.

*A poem written for the Fifth National Climate Assessment.*
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Margaret Plumley

# About This Report

The Global Change Research Act of 1990[1] mandates that the US Global Change Research Program (USGCRP) deliver a report to Congress and the President not less frequently than every four years that "integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings; analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."

The Fifth National Climate Assessment (NCA5) fulfills that mandate by delivery of this Assessment and provides the scientific foundation to support informed decision-making across the United States. By design, much of the development of NCA5 built upon the approaches and processes used to create the Fourth National Climate Assessment (NCA4),[2] with a goal of continuously advancing an inclusive, diverse, and sustained process for assessing and communicating scientific knowledge on the impacts, risks, and vulnerabilities associated with a changing global climate (App. 1).

The findings in this report are based on a comprehensive review and assessment of information sources determined to meet the standards and documentation required under the Information Quality Act and the Foundations for Evidence-Based Policymaking Act of 2018 (App. 2), including peer-reviewed literature, other literature, Indigenous Knowledge, other expert and local knowledge, and climate data processed and prepared for authors by NOAA's Technical Support Unit (TSU; see Guide to the Report section below and App. 3).

NCA5 was thoroughly reviewed by Federal Government experts, external experts, and the public multiple times throughout the report development process. An expert external review was performed by an ad hoc committee of the National Academies of Sciences, Engineering, and Medicine.[3] Additional information on the development of this Assessment can be found in Appendix 1: Assessment Development Process.

# Guide to the Report

## Intended Audience

The products of the US Global Change Research Program are designed to assist the Nation and the world in understanding, assessing, predicting, and responding to human-induced and natural processes of global change. National Climate Assessments synthesize scientific information and evaluate the state of the science on climate change to inform a broad audience of decision-makers across the country. These decision-makers include national, state, local, and Tribal governments, city planners, public health officials, adaptation specialists, nurses, farmers, business owners, community organizers, researchers, water utilities, ecosystem managers, educators, students, the media, and concerned individuals who need to make timely decisions about the climate impacts they are facing. National Climate Assessments make policy-neutral and policy-relevant information accessible and actionable by relying on the expert judgment of the report authors to determine what topics are included in each chapter, to describe what we know and where uncertainties remain, and to clearly communicate the risks, responses, and opportunities associated with climate change.

## Categories of Chapters and Their Scope

### Overview

The Overview chapter presents the major findings of the report alongside highlights drawn from across NCA5. This chapter provides a synthesis of material from the underlying report chapters.

### Physical Science Chapters

The Climate Trends and Earth Systems Processes chapters (Chs. 2, 3) assess how climate change affects physical Earth systems, with a focus on the United States, including observations and projections of climate change and discussion of how methods to understand changes in Earth systems have advanced since NCA4, which was released in November 2018.

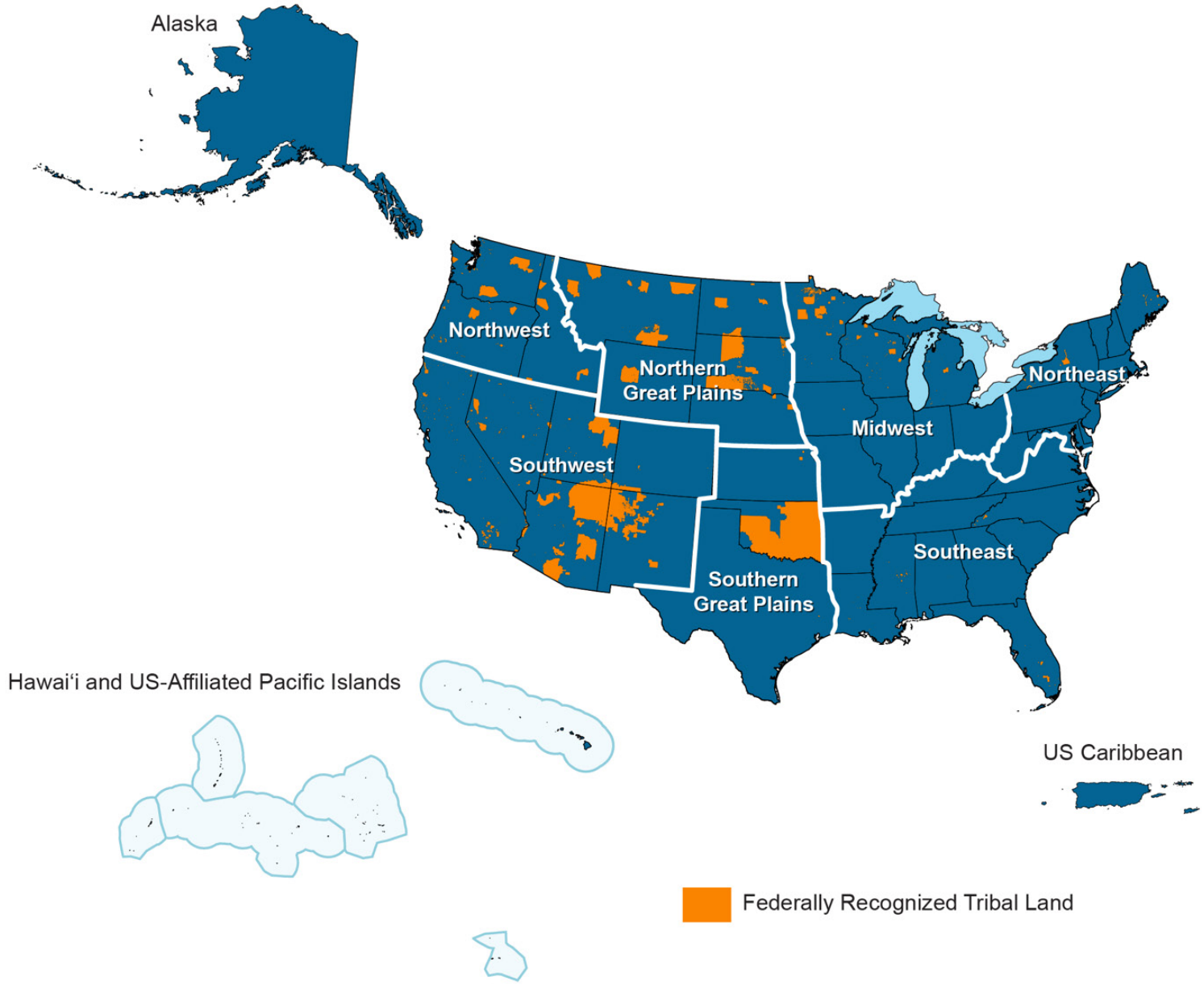
### National Topic Chapters

The national topic chapters (Chs. 4–20) summarize current and future risks related to climate change and what can be done to reduce those risks for a variety of societal and economic sectors of the United States. This Assessment builds on the range of topics covered in NCA4 by adding two new chapters: Economics (Ch. 19) and Social Systems and Justice (Ch. 20).

### Regional Chapters

The regional chapters (Chs. 21–30) assess current and future risks posed by climate change to each of the 10 NCA5 regions (Figure 1). These chapters provide detailed discussions of region-specific challenges, opportunities, and success stories for managing risks and impacts.

## Fifth National Climate Assessment Regions




**The Fifth National Climate Assessment explores subnational climate change risks, impacts, and responses in each of the 10 regions shown.**

Figure 1. The map shows the 10 US regions that correspond to the 10 regional chapters of the report (Chs. 21–30). The same regional boundaries are used in text and figures throughout the Assessment to provide regional-scale information where appropriate. Adapted from USGCRP 2018.[2]

### Response Chapters

The response chapters (Ch. 31: Adaptation and Ch. 32: Mitigation) assess the science of adapting to a changing climate, emissions reductions, and other efforts that together describe the US's existing and potential response to climate change, including benefits, trade-offs, targets, limitations, and best practices. The National Climate Assessment does not evaluate or recommend specific adaptation or mitigation policies.

### Focus on... Features

To better address critical and timely topics with themes that span the Assessment chapters, NCA5 pioneered a new feature: a set of five "Focus on..." boxes on important cross-cutting issues. High-priority topics were nominated by authors during early development of the report; final topics were approved for inclusion by the Federal Steering Committee. Authors from multiple NCA5 chapters assessed literature, coordinated cross-report discussions, and contributed text and figures to these features.

### Appendices

The first three appendices outline the development process, legal standards of scientific quality for assessing scientific information, and the climate scenarios and datasets used to support author assessment. Appendix 4 explores indicators of observed climate-related changes that support findings across NCA5. Appendix 5 is a glossary defining select terms in the context of how they are typically used across the Assessment.

### Glossary of Terms

Throughout the online version of the report, definitions of terms in the glossary (App. 5) are accessible via an interactive hover-over feature where text appears with a dotted underline. Any usage of a term that differs from the glossary definition is explicitly defined within chapter text.

### Artwork and Gallery

The NCA5 Art × Climate gallery showcases the work of visual artists across the country. These artworks and their accompanying descriptions speak to the causes and impacts of climate change, as well as the ways that people are responding. Submissions of visual art were collected through a public call, and finalists were selected by a jury panel of experts (App. 1). Artworks that appear throughout the PDF version of the report are denoted by a teal border. The artworks and associated artists' statements are not Assessment products and do not necessarily represent the views of the authors or USGCRP.

## Structure and Format of Chapter Content

### Key Messages

Chapters are centered around Key Messages, which are conclusions based on authors' expert judgment and synthesis of the assessed information sources. Many Key Messages present findings in the context of risks to natural and/or human systems. The text supporting each Key Message provides evidence, discusses implications, identifies intersections between systems or hazards, and presents examples of paths to greater resilience.

### Confidence and Likelihood

Evaluating confidence and likelihood is a key part of the assessment process. As in previous Assessments, NCA5 uses specific terms to convey information about scientific confidence and certainty associated with important findings, observations, and projections. Chapter authors use a range of calibrated terms adopted from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report[4] to describe the levels of **confidence** and, where appropriate, the assessment of **likelihood** associated with the statements in their Key Messages (Tables 1, 2).

- **Confidence** in a finding is based on the type, amount, quality, strength, and consistency of evidence; the skill, range, and consistency of methods to detect, evaluate, attribute, and interpret climate trends; and the degree of agreement across scientific information sources.
- **Likelihood** of a finding is based on measures of certainty expressed probabilistically; in other words, based on statistical analysis of observed or projected results or on the authors' expert judgment based on their assessment across scientific information sources.

These calibrated terms are presented in parentheses and set in *italics* after relevant phrases or sentences in the Key Messages. Statements in Key Messages that do not include either likelihood or confidence terms are intended as statements of fact. In some cases, calibrated likelihood assessments are also included in italics in the narrative text supporting Key Messages.

**Table 1. Calibrated Language for Confidence Assessment**

The NCA5 calibrated uncertainty language listed here and in Table 2 follows standards developed for the Intergovernmental Panel on Climate Change Fifth Assessment Report. The confidence levels listed below are used to reflect the quantity, quality, and degree of agreement across the evidence base underpinning an assessment finding. Source: Mastrandrea et al. 2011[4]

| Confidence Level | Definition |
|---|---|
| Very high | • Strong evidence (established theory, multiple sources, well-documented and accepted methods, etc.)<br>• High consensus |
| High | • Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.)<br>• Medium consensus |
| Medium | • Suggestive evidence (a few sources, limited consistency, methods emerging, etc.)<br>• Competing schools of thought |
| Low | • Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.)<br>• Disagreement or lack of opinions among experts |

**Table 2. Calibrated Language for Likelihood Assessment**

The calibrated uncertainty terms below are used to express a probabilistic assessment across the evidence base of the likelihood of observed or projected results. Source: Mastrandrea et al. 2011.[4]

| Likelihood Assessment | Numeric Probability of Outcome |
|---|---|
| Virtually certain | 99%–100% |
| Very likely | 90%–100% |
| Likely | 66%–100% |
| As likely as not | 33%–66% |
| Unlikely | 0%–33% |
| Very unlikely | 0%–10% |
| Exceptionally unlikely | 0%–1% |

### Traceable Accounts

Each chapter concludes with a section entitled Traceable Accounts, which provides information on the overall process used to develop the chapter as well as a separate Traceable Account section for each Key Message. These Traceable Accounts describe the supporting evidence behind each Key Message, the process and rationale authors used in reaching their conclusions, and the author team's expert assessment of the confidence in and, where applicable, likelihood of these conclusions. As such, Traceable Accounts provide information about the state of the science, document sources of uncertainty, identify research gaps, and allow traceability to data and resources.

Additional information on Key Messages and Traceable Accounts can be found in the Front Matter for NCA4.[2]

### Figures and Tables

Each figure in the report includes a figure number and title, a figure intent, and a caption. The figure title (embedded at the top of the figure) briefly describes what is shown in the figure, the figure intent (shown below the figure) provides a key takeaway message of the figure, and the caption (shown below the figure intent) provides additional information on how to interpret the elements of the figure. Where original figures have been developed for the Assessment, the figure credit listed at the end of the caption notes the affiliation of the NCA5 authors or contributors responsible for the development of the figure.

Each figure and some tables are accompanied by a metadata survey, which can be accessed in the online version of the report by clicking on the eyeball icon above the figure or table (see the table below for explanations of additional icons used throughout the report). The metadata survey describes data sources, figure or table development methods, copyright information, and other important documentation. All figures that appear in the online version of the report are also accompanied by alternative text for screen readers.

| Icon | Description |
|---|---|
| | Share a chapter, chapter section, figure, table, box, or other content element |
| | Access metadata for a table or figure |
| | Download a figure |
| | Access additional information about a figure, table, or box in the Climate Resilience Toolkit |
| | Access additional information about a figure, table, or box in the NCA5 Atlas |

## Metrics and Definitions Used Across the Report

### Economic Estimates

Unless otherwise noted, economic estimates in this report have been converted to 2022 US dollars using the US Bureau of Economic Analysis's Implicit Price Deflators for Gross Domestic Product, Table 1.1.9.[12] Where documented in the underlying literature, discount rates in specific estimates in this Assessment are noted next to those projections.

### Use of Scenarios

Climate modeling experts develop global climate projections for a range of realistic futures. These projections capture variables such as the relationship between human behavior, greenhouse gas (GHG) emissions, the Earth system processes and responses to changes in concentration of GHGs in our atmosphere and oceans, and resulting impacts, including temperature change and sea level rise. Because there are

uncertainties inherent in all of these factors—especially human behavior and the choices that determine emissions levels—the resulting range of projections are not predictions but instead reflect multiple potential pathways for our collective future (Ch. 2). The scenarios do not have relative likelihoods assigned and are all plausible futures.

NCA5 authors were advised to assess the full range of scenarios available. While use of specific scenarios was not mandated across the report, authors were encouraged to report impacts under more than one scenario in order to describe a range of possible outcomes. Few climate projections extend past 2100, limiting the information available for authors to evaluate trends 100 years into the future (Box A3.1).

To help communicate author findings effectively, the naming convention with simplified summary descriptions shown in Table 3 is used across the report to describe the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) used in Phases 5 and 6 of the Coupled Model Intercomparison Project (CMIP5 and CMIP6), respectively. Scenarios other than those described in Table 3 are referred to by name.

**Table 3. Descriptive Terms for Common Climate Scenarios Used in NCA5**

This table summarizes the terms used to describe scenarios from Phases 5 and 6 of the Coupled Model Intercomparison Project (CMIP5 and CMIP6). This standardized terminology is used throughout the report when discussing scenarios to facilitate easier comparison by readers. Sources: Arias et al. 2021; Gidden et al. 2019; Meinshausen et al. 2020; O'Neil et al. 2017; Riahi et al. 2017; van Vuuren et al. 2011 [5,6,7,8,9,10]

| Climate Scenario Descriptor | CMIP5 | CMIP6 | Summary |
|---|---|---|---|
| Very High Scenario | RCP8.5 | SSP5-8.5 | Among the scenarios described here, these reflect the highest range of carbon dioxide ($CO_2$) emissions and no mitigation. Total annual global $CO_2$ emissions in 2100 are quadruple emissions in 2000 (RCP8.5 and SSP5-8.5). Population growth in 2100 doubles from 2000 in RCP8.5, but the SSP5-8.5 population remains relatively stable, with approximately 13% growth in 2100 from 2005. Both scenarios include fossil fuel development, but SSP5-8.5 has higher economic growth than RCP8.5. |
| High Scenario | RCP6.0 | SSP3-7.0 | These scenarios reflect high $CO_2$ emissions with limited (RCP6.0) or no (SSP3-7.0) mitigation. Total annual $CO_2$ emissions in 2100 are more than 75% higher than in 2000 in RCP6.0, and triple that of 2000 emissions in SSP3-7.0. Compared to 2000, both scenarios include expanded fossil fuel development and population growth but slow economic growth. |
| Intermediate Scenario | RCP4.5 | SSP2-4.5 | These scenarios reflect reductions in $CO_2$ emissions from current levels. Total annual $CO_2$ emissions in 2100 are 46% (RCP4.5) and 67% (SSP2-4.5) less than the year 2000. Mitigation efforts include low-carbon technology (SSP2-4.5) and expanded renewable energy compared to 2000 (RCP 4.5). |
| Low Scenario | RCP2.6 | SSP1-2.6 | These scenarios reflect rapidly declining and net-negative $CO_2$ emissions (with $CO_2$ removal from the atmosphere exceeding human-caused emissions) by 2100. Mitigation efforts include increased renewable energy. Adaptive capacity reflects effective governance institutions, reduced inequality, and international cooperation (SSP1-2.6). |
| Very Low Scenario | n/a | SSP1-1.9 | Among the scenarios described here, SSP1-1.9 reflects the greatest reduction in global greenhouse gas emissions and substantial $CO_2$ removal from the atmosphere. Total annual $CO_2$ emissions have a steeper decline than SSP1-2.6, dropping by more than 145% by 2100 compared to 2000. Mitigation efforts include a shift to nuclear and renewable energy and sustainable land use. Adaptive capacity benefits from international cooperation and sharing of technology. |

## Box 1. Global Warming Levels Measure How Much the Planet Has Warmed

In this report, the term "global warming level" is used to describe the level of global temperature increase relative to preindustrial temperatures conditions (the 1850–1900 average). A given global warming level is reached when global annual warming, defined by the average temperature over multiple decades, exceeds a specified level. Although this Assessment primarily reports temperatures in Fahrenheit, global warming levels are usually reported and more widely known in degrees Celsius. For example, the Paris Agreement set a goal of holding the increase in global average temperature to "well below" 2°C (3.6°F) and pursuing efforts to limit the temperature increase to 1.5°C (2.7°F) above preindustrial levels. Thus, global warming levels are typically defined in this report with their Celsius value first and their Fahrenheit value in parentheses.

Internal variability in the climate system means that even as the world rapidly warms, some years will be hotter and some years will be cooler than the multidecadal average. This annual variability means that even if a single year occurs in which Earth is 1.5°C (2.7°F) hotter than the preindustrial average, the 1.5°C global warming level has not necessarily been reached. Conversely, such variability also means that climate impacts projected to occur at a given global warming level may occur earlier than expected, before that level is reached in terms of multidecadal average temperatures. In addition, temperatures in some parts of the world are warmer or cooler than the global average. For example, a global warming level of 2°C (3.6°F) would result in regional temperatures in parts of the United States that are more than 2°C above preindustrial levels (Figure 1.14).

Global warming levels are not thresholds; they do not represent "safe" levels of warming, nor does exceeding a particular global warming level mean that it is too late to slow or halt many of the impacts of climate change by reducing greenhouse gas emissions. Continued action to reduce emissions can avoid the worst impacts of climate change and provide valuable benefits to society and ecosystems no matter what global warming level is reached or exceeded. At regional or local scales, climate impacts, such as increased risks of extreme weather, depend on changes to underlying drivers like local temperatures and rainfall. These changes in turn depend on the level of global warming. The level of global warming depends on future emissions, which depend on human actions. This means that future projections are conditional: when or if Earth reaches a particular level of warming is largely dependent on human choices.

To support decision-making related to future sea level risks, a set of five specific trajectories were selected to cover a range of plausible future global mean sea level conditions. Table 4 displays the naming convention used by NCA5 authors to describe the range of possible rise in global and US sea levels. Although the sea level rise scenarios in Table 4 were developed using global warming levels derived from the Shared Socioeconomic Pathways and there are similarities in the naming conventions (e.g., low, intermediate, high), they have distinct definitions and are used in different ways from the climate scenarios shown in Table 3 (App. 3).[11]

Additional information on scenarios can be found in the Overview and in Appendix 3.

**Table 4. Descriptive Terms for Common Sea Level Rise Scenarios Used in NCA5**

Future global mean sea level rise and sea level rise along United States coastline are shown for five scenarios in feet (and meters), relative to a 2000 baseline. The US values shown in the right half of the table are averaged across the US coastal regions, including the contiguous US, Alaska, Hawai'i and the US-Affiliated Pacific Islands, and the US Caribbean. The national values shown in the table differ substantially from regional values. For example, sea level rise is higher in the Gulf Coast and lower or even negative in some parts of Alaska. In the next 30 years (2020–2050), sea level along the contiguous US coasts is expected to rise 0.92 feet (0.28 m), the same amount of sea level rise observed over the last 100 years (1920–2020). See Chapter 9 for regional sea level information. Adapted from Sweet et al. 2022.[11]

| Sea Level Rise Scenario Descriptor | Global Mean Sea Level | | | United States | | |
|---|---|---|---|---|---|---|
| Year | 2050 | 2100 | 2150 | 2050 | 2100 | 2150 |
| Low | 0.49 (0.15) | 0.98 (0.3) | 1.31 (0.4) | 0.59 (0.18) | 0.98 (0.3) | 1.64 (0.5) |
| Intermediate-Low | 0.66 (0.20) | 1.64 (0.5) | 2.62 (0.8) | 0.75 (0.23) | 1.64 (0.5) | 2.95 (0.9) |
| Intermediate | 0.92 (0.28) | 3.28 (1.0) | 6.23 (1.9) | 0.89 (0.27) | 3.28 (1.0) | 6.89 (2.1) |
| Intermediate-High | 1.21 (0.37) | 4.92 (1.5) | 8.86 (2.7) | 1.12 (0.34) | 4.92 (1.5) | 8.86 (2.7) |
| High | 1.41 (0.43) | 6.56 (2.0) | 12.14 (3.7) | 1.38 (0.42) | 6.56 (2.0) | 12.46 (3.8) |

# Key Advances Since the Fourth National Climate Assessment

Advances since the publication of the Fourth National Climate Assessment (2017–2018) have led to new understanding of the changing climate system, the resulting impacts on society, and approaches to reduce risks. See Appendix 1 for advances in the development process of NCA5.

## Physical Climate Science

**Reduced uncertainty:** New observations combined with improved modeling provide multiple lines of evidence supporting advances in understanding and projections of climate change. Improved understanding has significantly narrowed the estimated range of global warming expected from a doubling of $CO_2$ in the atmosphere to 4.5°–7.2°F (2.5°–4.0°C). (KMs 3.2, 3.3)

**Improved attribution:** Advances have increased confidence in the linkages between many weather disasters and climate change, and scientists can now estimate the role of climate change in some types of extreme events in real time. For example, climate change was estimated to have increased the rainfall of Hurricane Harvey in 2017 by about 15% to 20%. (Ch. 2; Introduction; KMs 2.2, 3.3)

**Incorporating socioeconomics:** New model projections are based on policy-relevant scenarios that span plausible future social and economic development pathways (Table 3). These scenarios allow for a deeper exploration of the interactions between development and emissions pathways, as well as technology pathways to reach net-zero emissions goals. (KMs 2.3, 3.2, 6.3, 32.2; App. 3)

**New models:** The latest generation of Earth system models incorporates more detailed simulations of the physical climate system and provides improved understanding of how regional-scale processes will change with warming. (KM 3.3)

## Risks and Impacts

**Connecting justice:** More information is available on disproportionate climate change impacts on overburdened communities, including a better understanding of how climate impacts exacerbate, and are exacerbated by, social inequities. (KMs 4.2, 9.2, 11.2, 12.2, 14.3, 15.2, 16.1, 19.1, 21.3, 26.4, 27.1, 31.2; Introductions in Chs. 16, 17, 20)

**Untangling interconnections:** Observations and enhanced modeling highlight the compounding and cascading effects of climate change on interconnected food, energy, and water systems. Understanding of how climate change affects national security, sustainable and equitable development, and disaster risk reduction and recovery has improved. (Chs. 17, 18; KMs 4.2, 5.2, 6.1, 6.2, 12.2, 19.3)

**Damages by degrees:** Improved understanding of the risks human and environmental systems face under each additional increment of global warming has helped scientists quantify potential damages to health, ecosystems, livelihoods, and the economy (see Box 1). (Ch. 8, Introduction; KM 19.1)

## Responses

**Sophisticated support:** Improved tools, data, and climate projections needed to support adaptation, mitigation, and resilience measures are becoming more widely available, including advancements in quantifying the economic, health, and environmental benefits from climate actions and better documentation of how the benefits and burdens of investments are distributed. (Ch. 4, Introduction; KMs 5.3, 7.3, 11.3, 12.2, 13.2, 31.5, 32.4; Box 17.1)

**Understanding people:** The social sciences are providing new insights into how people experience climate change and how climate actions are understood, communicated, and implemented. Increased documentation of institutional changes, partnerships, knowledge sharing, and sustainable financing options are supporting climate action at multiple levels of government. (KMs 12.3, 31.4, 31.6; Ch. 20)

**Indigenous Knowledge:** Growing efforts to integrate Indigenous Knowledge in community adaptation actions build on accumulated knowledge that has enabled Indigenous Peoples to adapt to environmental change for millennia. (KMs 16.3, 25.5, 27.6, 28.2, 29.5, 30.5; Box 27.2)

**Real-world examples:** More examples of adaptation in practice, such as green infrastructure, nature-based solutions, and changes in governance and financing, are now available. Cities and states that have implemented adaptation actions are sharing best practices and aiding cooperation, and many communities are learning from climate change responses led by Tribal and Indigenous Peoples. (KMs 12.3, 16.3; Ch. 31)

## Reporting Suspected Errata

In case of a suspected error in this report, please send an email containing the following information to nca-errata-group@usgcrp.gov:

Your full name
Your organization (if applicable)
Chapter and section (e.g., chapter title, Key Message number, or figure number)
An explanation of your concern

# References


1. Global Change Research Act of 1990. 101st Congress, Pub. L. No. 101-606, 104 Stat. 3096–3104, November 16, 1990. https://www.congress.gov/bill/101st-congress/senate-bill/169/text

2. USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/nca4.2018

3. National Academies of Sciences, Engineering, and Medicine, 2023: *Review of the Draft Fifth National Climate Assessment*. The National Academies Press, Washington, DC, 346 pp. https://doi.org/10.17226/26757

4. Mastrandrea, M.D., K.J. Mach, G.-K. Plattner, O. Edenhofer, T.F. Stocker, C.B. Field, K.L. Ebi, and P.R. Matschoss, 2011: The IPCC AR5 guidance note on consistent treatment of uncertainties: A common approach across the working groups. *Climatic Change*, **108** (4), 675. https://doi.org/10.1007/s10584-011-0178-6

5. Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld, 2021: Technical summary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 33–144. https://doi.org/10.1017/9781009157896.002

6. Gidden, M.J., K. Riahi, S.J. Smith, S. Fujimori, G. Luderer, E. Kriegler, D.P. van Vuuren, M. van den Berg, L. Feng, D. Klein, K. Calvin, J.C. Doelman, S. Frank, O. Fricko, M. Harmsen, T. Hasegawa, P. Havlik, J. Hilaire, R. Hoesly, J. Horing, A. Popp, E. Stehfest, and K. Takahashi, 2019: Global emissions pathways under different socioeconomic scenarios for use in CMIP6: A dataset of harmonized emissions trajectories through the end of the century. *Geoscientific Model Development*, **12** (4), 1443–1475. https://doi.org/10.5194/gmd-12-1443-2019

7. Meinshausen, M., Z.R.J. Nicholls, J. Lewis, M.J. Gidden, E. Vogel, M. Freund, U. Beyerle, C. Gessner, A. Nauels, N. Bauer, J.G. Canadell, J.S. Daniel, A. John, P.B. Krummel, G. Luderer, N. Meinshausen, S.A. Montzka, P.J. Rayner, S. Reimann, S.J. Smith, M. van den Berg, G.J.M. Velders, M.K. Vollmer, and R.H.J. Wang, 2020: The Shared Socio-economic Pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, **13** (8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

8. O'Neill, B.C., E. Kriegler, K.L. Ebi, E. Kemp-Benedict, K. Riahi, D.S. Rothman, B.J. van Ruijven, D.P. van Vuuren, J. Birkmann, K. Kok, M. Levy, and W. Solecki, 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

9. Riahi, K., D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J.C. Cuaresma, S. Kc, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J.C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, and M. Tavoni, 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

10. van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, and S.K. Rose, 2011: The Representative Concentration Pathways: An overview. *Climatic Change*, **109** (1), 5. https://doi.org/10.1007/s10584-011-0148-z

11. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

12. BEA. 2023: Table 1.1.9. Implicit Price Deflators for Gross Domestic Product. U.S. Department of Commerce, Bureau of Economic Analysis. https://apps.bea.gov/iTable/?reqid=19&step=3&isuri=1&1921=survey&1903=13

# Overview: Understanding Risks, Impacts, and Responses

# Chapter 1. Overview: Understanding Risks, Impacts, and Responses

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Tammy West

The Fifth National Climate Assessment documents observed and projected vulnerabilities, risks, and impacts associated with climate change across the United States and provides examples of response actions underway in many communities. This Overview presents highlights from the Assessment, providing summary findings and a synthesis of material from the underlying chapters. Curly brackets indicate cross-references to full chapters (e.g., {Ch. 2}), Key Messages (e.g., {2.1}), figures (e.g., {Figure 32.8}), and other text elements.

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Margaret Plumley

# How the United States Is Addressing Climate Change

The effects of human-caused climate change are already far-reaching and worsening across every region of the United States. Rapidly reducing greenhouse gas emissions can limit future warming and associated increases in many risks. Across the country, efforts to adapt to climate change and reduce emissions have expanded since 2018, and US emissions have fallen since peaking in 2007. However, without deeper cuts in global net greenhouse gas emissions and accelerated adaptation efforts, severe climate risks to the United States will continue to grow.

## Future climate change impacts depend on choices made today

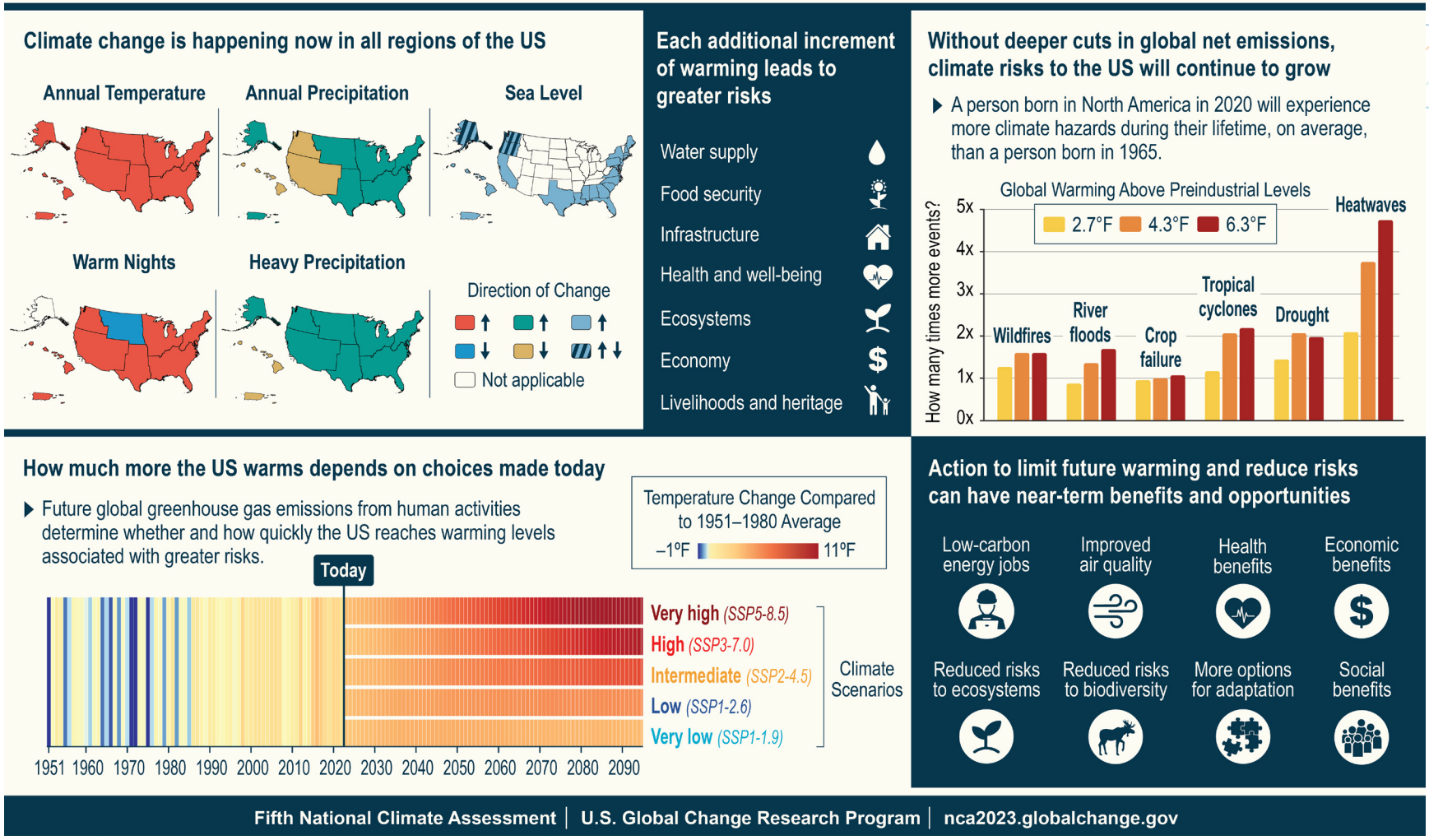
The more the planet warms, the greater the impacts. Without rapid and deep reductions in global greenhouse gas emissions from human activities, the risks of accelerating sea level rise, intensifying extreme weather, and other harmful climate impacts will continue to grow. Each additional increment of warming is expected to lead to more damage and greater economic losses compared to previous increments of warming, while the risk of catastrophic or unforeseen consequences also increases. {2.3, 19.1}

However, this also means that each increment of warming that the world avoids—through actions that cut emissions or remove carbon dioxide ($CO_2$) from the atmosphere—reduces the risks and harmful impacts of climate change. While there are still uncertainties about how the planet will react to rapid warming, the degree to which climate change will continue to worsen is largely in human hands. {2.3, 3.4}

In addition to reducing risks to future generations, rapid emissions cuts are expected to have immediate health and economic benefits (Figure 1.1). At the national scale, the benefits of deep emissions cuts for current and future generations are expected to far outweigh the costs. {2.1, 2.3, 13.3, 14.5, 15.3, 32.4; Ch. 2, Introduction}

Taelyn B.

## Climate Change Risks and Opportunities in the US




**Climate change presents risks while action to limit warming and reduce risks presents opportunities for the US.**

**Figure 1.1**. (**top left**) Changes in multiple aspects of climate are apparent in every US region. The five maps present observed changes for five temperature, precipitation, and sea level rise metrics: 1) warming is apparent in every region (based on changes in annual average temperature in 2002–2021 compared to the 1901–1960 average for the contiguous United States, Hawai'i, and Puerto Rico and to 1925–1960 for Alaska); 2) the number of warm nights per year (days with minimum temperatures at or above 70°F in 2002–2021 compared to 1901–1960) is increasing everywhere except the Northern Great Plains, where they have decreased, and in Alaska, where nights above 70°F are not common; 3) average annual precipitation is increasing in most regions, except in the Northwest, Southwest, and Hawai'i, where precipitation has decreased (same time periods as annual average temperature); 4) heavy precipitation events are increasing everywhere except Hawai'i and the US Caribbean, where there has been a decrease (trends over the period 1958–2021); and 5) relative sea levels are increasing along much of the US coast except in Oregon, Washington, and Alaska, where there is a mix of both increases and decreases (trends over 1990–2020). {2.2, 9.1; Figures 2.4, 2.5, 2.7, 2.8}

(**top center**) Every fraction of a degree of additional warming will lead to increasing risks across multiple sectors in the US (see Table 1.2 and "Current and Future Climate Risks to the United States" below). Without rapid, substantial reductions in the greenhouse gases that cause global warming, these climate risks in the US are expected to increase.

(**top right**) People born in North America in 2020, on average, will be exposed to more climate-related hazards compared to people born in 1965. How many more extreme climate events current generations experience compared to previous generations will depend on the level of future warming. {Figure 15.4}

(**bottom left**) This climate stripes chart shows the observed changes in US annual average surface temperature for 1951–2022 and projected changes in temperature for 2023–2095 for five climate scenarios, ranging from a very high scenario, where greenhouse gas emissions continue to increase through most of the century, to a very low scenario, where emissions decline rapidly, reaching net zero by around midcentury (see Figure 1.4 and Table 3 in the Guide to the Report). Each vertical stripe represents the observed or projected change in temperature for a given year compared to the 1951–1980 average; changes are averaged over all 50 states and Puerto Rico but do not include data for the US-Affiliated Pacific Islands and the US Virgin Islands (see also Figure 1.13).

(**bottom right**) Although climate benefits from even the most aggressive emissions cuts may not be detectable before the middle of the century, there are many other potential near-term benefits and opportunities from actions that reduce greenhouse gas emissions. {2.3, 8.3, 10.3, 13.3, 14.5, 15.3, 19.1, 31.3, 32.4}

Figure credits: (top left, top center, top right, bottom right) USGCRP, USGCRP/ICF, NOAA NCEI, and CISESS NC; (bottom left) adapted from panel (c) of Figure SPM.1 in IPCC 2023.

## Box 1.1. Mitigation, Adaptation, and Resilience

Throughout this report, three important terms are used to describe the primary options for reducing the risks of climate change:

- **Mitigation**: Measures to reduce the amount and rate of future climate change by reducing emissions of heat-trapping gases (primarily carbon dioxide) or removing greenhouse gases from the atmosphere.
- **Adaptation**: The process of adjusting to an actual or expected environmental change and its effects in a way that seeks to moderate harm or exploit beneficial opportunities.
- **Resilience**: The ability to prepare for threats and hazards, adapt to changing conditions, and withstand and recover rapidly from adverse conditions and disruptions.

James Keul

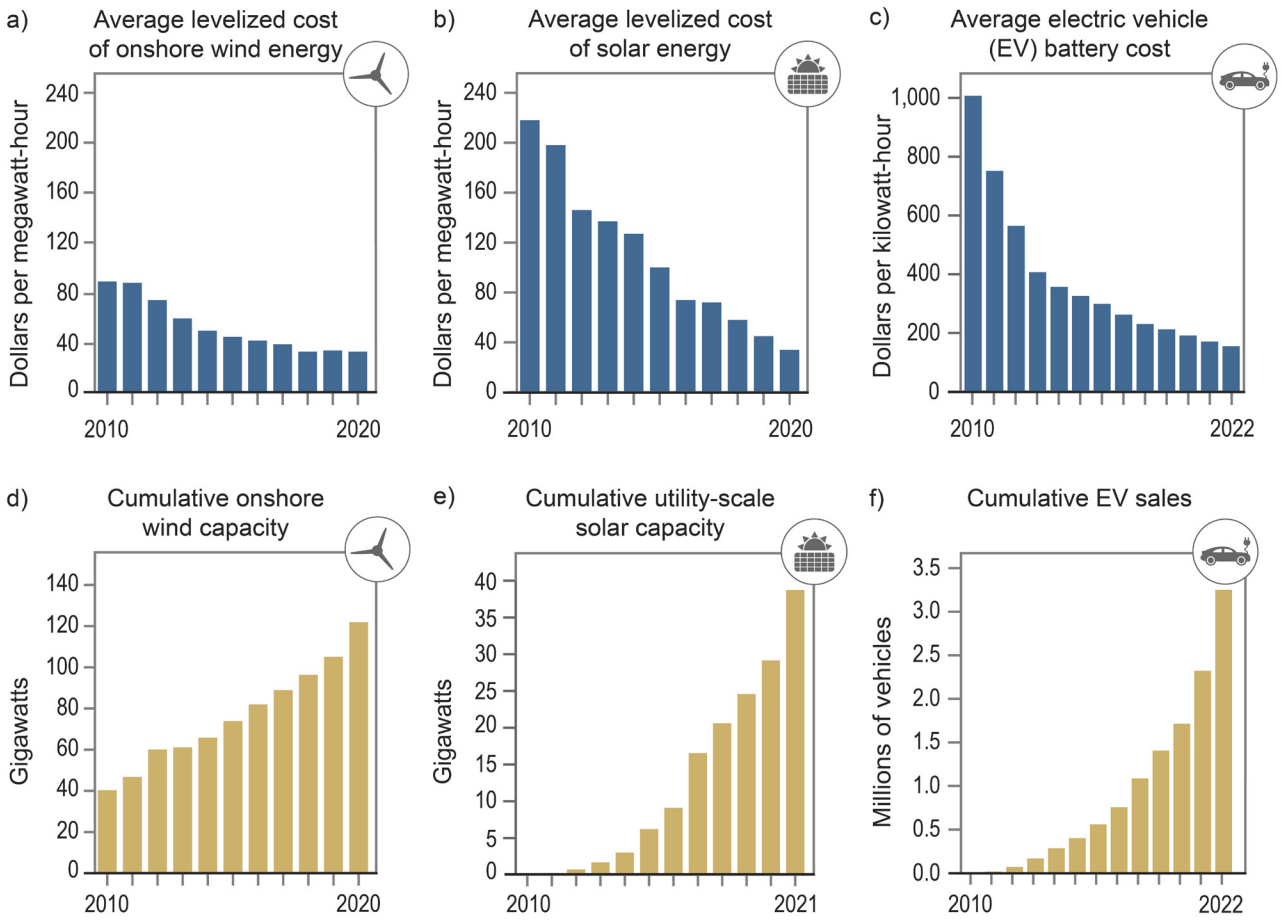
## US emissions have decreased, while the economy and population have grown

Annual US greenhouse gas emissions fell 12% between 2005 and 2019. This trend was largely driven by changes in electricity generation: coal use has declined, while the use of natural gas and renewable technologies has increased, leading to a 40% drop in emissions from the electricity sector. Since 2017, the transportation sector has overtaken electricity generation as the largest emitter. {11.1, 13.1, 32.1; Figures 32.1, 32.3}

As US emissions have declined from their peak in 2007, the country has also seen sustained reductions in the amount of energy required for a given quantity of economic activity and the emissions produced per unit of energy consumed. Meanwhile, both population and per capita GDP have continued to grow. {32.1; Figures 32.1, 32.2}

Recent growth in the capacities of wind, solar, and battery storage technologies is supported by rapidly falling costs of zero- and low-carbon energy technologies, which can support even deeper emissions reductions. For example, wind and solar energy costs dropped 70% and 90%, respectively, over the last decade, while 80% of new generation capacity in 2020 came from renewable sources (Figures 1.2, 1.3). {5.3, 12.3, 32.1, 32.2; Figure A4.17}

Across all sectors, innovation is expanding options for reducing energy demand and increasing energy efficiency, moving to zero- and low-carbon electricity and fuels, electrifying energy use in buildings and transportation, and adopting practices that protect and improve natural carbon sinks that remove and store $CO_2$ from the atmosphere, such as sustainable agricultural and land-management practices. {11.1, 32.2, 32.3; Boxes 32.1, 32.2; Focus on Blue Carbon}




## Historical Trends in Unit Costs and Deployment of Low-Carbon Energy Technologies in the United States

**Increasing capacities and decreasing costs of low-carbon energy technologies are supporting efforts to further reduce emissions.**

**Figure 1.2.** Costs of onshore wind (**a**), solar photovoltaics (**b**), and electric vehicle (EV) batteries (**c**) have decreased sharply since 2000 (data shown here start in 2010), as the cumulative capacities of wind and solar generation (**d** and **e**) and the cumulative number of EVs sold (**f**) have increased. {Figure 32.8} Figure credit: Electric Power Research Institute, National Renewable Energy Laboratory, NOAA NCEI, and CISESS NC.

## Accelerating advances in adaptation can help reduce rising climate risks

As more people face more severe climate impacts, individuals, organizations, companies, communities, and governments are taking advantage of adaptation opportunities that reduce risks. State climate assessments and online climate services portals are providing communities with location- and sector-specific information on climate hazards to support adaptation planning and implementation across the country. New tools, more data, advancements in social and behavioral sciences, and better consideration of practical experiences are facilitating a range of actions (Figure 1.3). {7.3, 12.3, 21.4, 25.4, 31.1, 31.5, 32.5; Table 31.1}

Actions include:

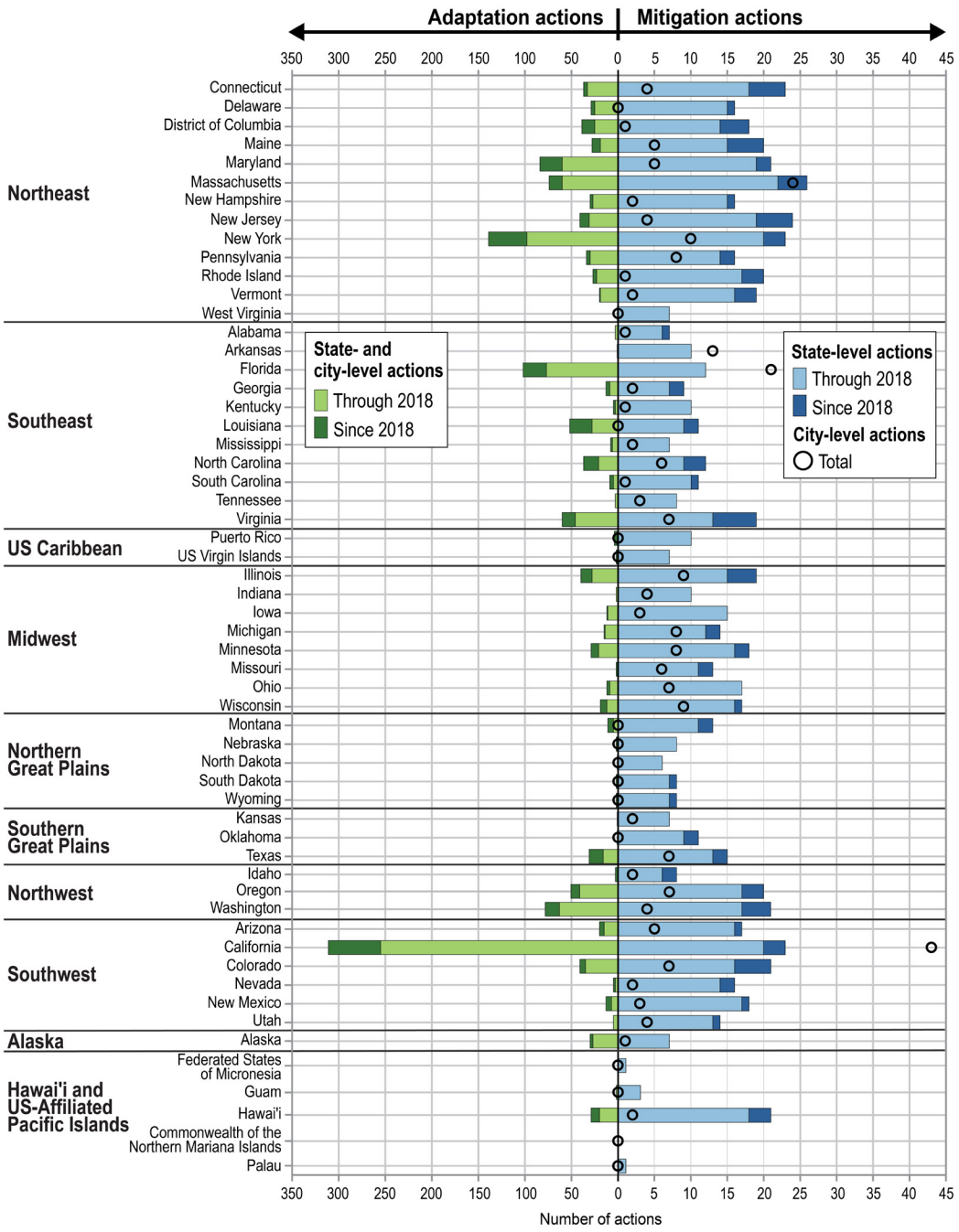
- Implementing nature-based solutions—such as restoring coastal wetlands or oyster reefs—to reduce shoreline erosion {8.3, 9.3, 21.2, 23.5}
- Upgrading stormwater infrastructure to account for heavier rainfall {4.2}
- Applying innovative agricultural practices to manage increasing drought risk {11.1, 22.4, 25.5}
- Assessing climate risks to roads and public transit {13.1}
- Managing vegetation to reduce wildfire risk {5.3}
- Developing urban heat plans to reduce health risks from extreme heat {12.3, 21.1, 28.4}
- Planning relocation from high-risk coastal areas {9.3}

Despite an increase in adaptation actions across the country, current adaptation efforts and investments are insufficient to reduce today's climate-related risks and keep pace with future changes in the climate. Accelerating current efforts and implementing new ones that involve more fundamental shifts in systems and practices can help address current risks and prepare for future impacts (see "Mitigation and adaptation actions can result in systemic, cascading benefits" below). {31.1, 31.3}

Pam DeChellis

## Climate action has increased in every region of the US

Efforts to adapt to climate change and reduce net greenhouse gas emissions are underway in every US region and have expanded since 2018 (Figure 1.3; Table 1.1). Many actions can achieve both adaptation and mitigation goals. For example, improved forest- or land-management strategies can both increase carbon storage and protect ecosystems, and expanding renewable energy options can reduce emissions while also improving resilience. {31.1, 32.5}




## US Adaptation and Mitigation Actions

**Cities and states are acting on climate change, with a substantial increase in new activities underway since 2018.**

**Figure 1.3.** Since 2018, city- and state-level adaptation plans and actions (**green bars**, left) increased by 32%, complemented by a 14% increase in the total number of new state-level mitigation activities (**blue bars**, right; 69% have updated their policies). In 2021 there were 271 city-level mitigation actions in place (**open circles**, right), according to the Global Climate Action Tracker. Renewable energy and energy efficiency projects on Tribal lands have also expanded (not shown). {31.1, 32.5; Figure 16.4; Table 1.1} Figure credit: US Army Corps of Engineers, EPA, Pennsylvania State University, NOAA NCEI, and CISESS-NC.

Climate adaptation and mitigation efforts involve trade-offs, as climate actions that benefit some or even most people can result in burdens to others. To date, some communities have prioritized equitable and inclusive planning processes that consider the social impacts of these trade-offs and help ensure that affected communities can participate in decision-making. As additional measures are implemented, more widespread consideration of their social impact can help inform decisions around how to distribute the outcomes of investments. {12.4, 13.4, 20.2, 21.3, 21.4, 26.4, 27.1, 31.2, 32.4, 32.5; Box 20.1}

**Table 1.1. Climate Actions Are Taking Place Across All US Regions**

Examples of recent local adaptation, resilience, and mitigation actions around the country follow.

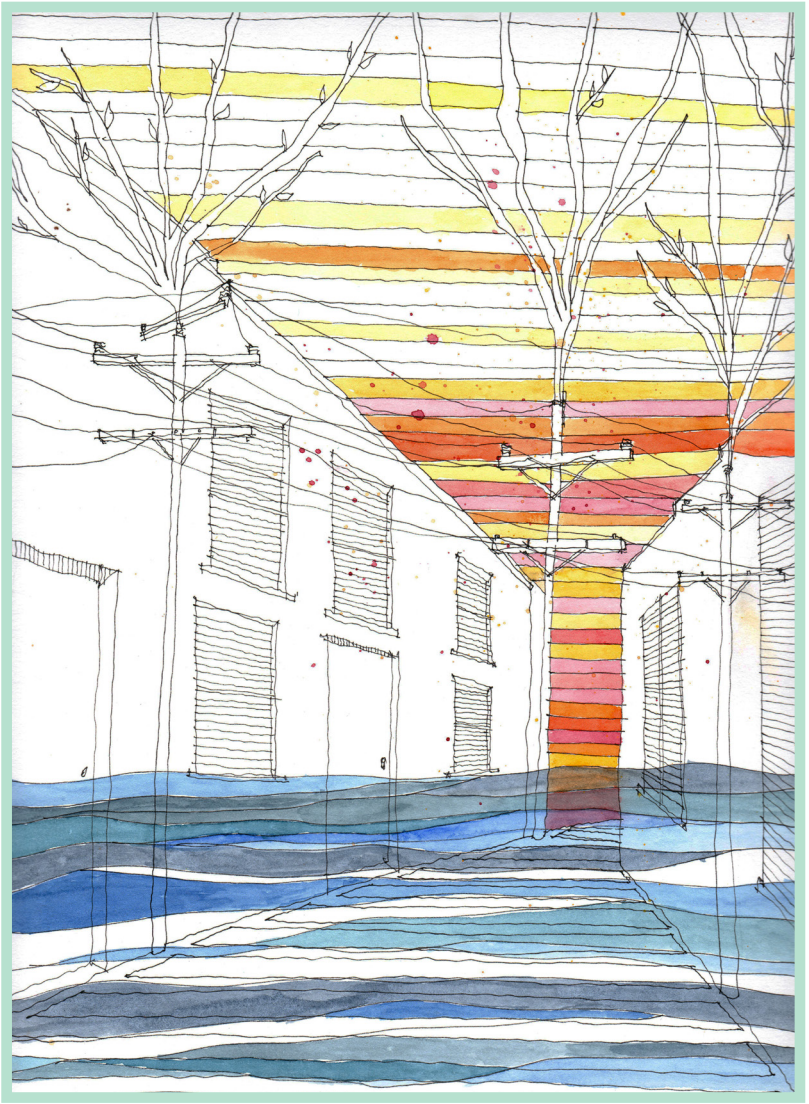
| Region | Action |
|---|---|
| **Northeast** | The 2022 stormwater code in Pittsburgh, Pennsylvania, requires new developments to plan for projected increases in heavy rainfall under climate change rather than building to historical rainfall amounts. In 2021, the city also committed to achieve carbon neutrality by 2050. {Box 21.1} |
| **Southeast** | Following repeated flooding from multiple hurricanes, measures to reduce flood risk in Princeville, North Carolina, include buyouts, elevating homes, and building housing that meets local flood standards. In Orlando, Florida, the city and businesses are adopting commercial building energy-efficiency requirements and electric vehicle readiness policies and have used wastewater and food scraps from parks and resorts to generate renewable biogas. {Boxes 22.1, 32.3} |
| **US Caribbean** | Many community-based organizations in Puerto Rico have undertaken actions to advance adaptation, social transformation, and sustainable development. These organizations work to expand renewable energy and equitable access to energy resources, prepare for disasters, restore ecosystems, strengthen agriculture and food security, and protect public health. {23.5} |
| **Midwest** | A wetland creation project in Ashtabula, Ohio, restored habitat displaced by shoreline development, improving coastal protection for the port on Lake Erie. In Michigan, some state forestlands are being managed to bolster carbon storage and to support recreation and wildlife habitat. {24.2, 24.4; Figure 24.9} |
| **Northern Great Plains** | The Nebraska Natural Resources Conservation Service supported farmers in testing soil health and evaluating soil management practices that promote climate adaptation. Across the region, wind electricity generation tripled between 2011 and 2021, with a growing number of Tribes leading the Nation's renewable energy transition by installing wind, solar, and hydropower. {25.3, 25.5; Box 25.3} |
| **Southern Great Plains** | Texas- and Kansas-based groups are supporting soil and land management practices that increase carbon storage while protecting important ecosystems. Wind and solar energy generation and battery storage capacities have also grown, with the region accounting for 42% of national wind-generated electricity in 2022. {26.2} |
| **Northwest** | The Confederated Tribes of the Colville Reservation are prioritizing carbon capture in their forest and timber management efforts, leading to improved air and water quality and wildlife habitat as well as preservation of cultural areas and practices. {27.3} |
| **Southwest** | In response to severe drought, seven Colorado River basin states, the US and Mexican governments, and Indigenous Peoples are collaborating to improve water conservation and develop adaptation solutions. Dozens of cities are committed to emissions reductions; for instance, Phoenix is on track to meet a 2030 goal of 50% reduction in greenhouse gas emissions from 2018 levels. {Ch. 28, Introduction; Box 28.1} |
| **Alaska** | To address climate threats to traditional foods, the Chugach Regional Resources Commission is integrating Indigenous Knowledge and Western scientific methods in its adaptation efforts, including weekly water sampling for harmful algal blooms and restoring clam populations. Kelp farming is also being developed to reduce the effects of ocean acidification, serve as a carbon sink, and generate income. {29.7; Box 29.7} |
| **Hawai'i and US-Affiliated Pacific Islands** | The Kaua'i Island Utility Cooperative achieved a 69.5% renewable portfolio standard in 2021, and the island is occasionally 100% renewably powered during midday hours; it is projected to achieve a 90% renewable portfolio by 2026. Guam, the Republic of the Marshall Islands, the Federated States of Micronesia, and Palau plan to use blue carbon ecosystems to offset emissions while also protecting coastal infrastructure. {30.3; Box 30.3} |

## Meeting US mitigation targets means reaching net-zero emissions

The global warming observed over the industrial era is unequivocally caused by greenhouse gas emissions from human activities—primarily burning fossil fuels. Atmospheric concentrations of carbon dioxide ($CO_2$)—the primary greenhouse gas produced by human activities—and other greenhouse gases continue to rise due to ongoing global emissions. Stopping global warming would require both reducing emissions of $CO_2$ to net zero and rapid and deep reductions in other greenhouse gases. Net-zero $CO_2$ emissions means that $CO_2$ emissions decline to zero or that any residual emissions are balanced by removal from the atmosphere. {2.3, 3.1; Ch. 32}

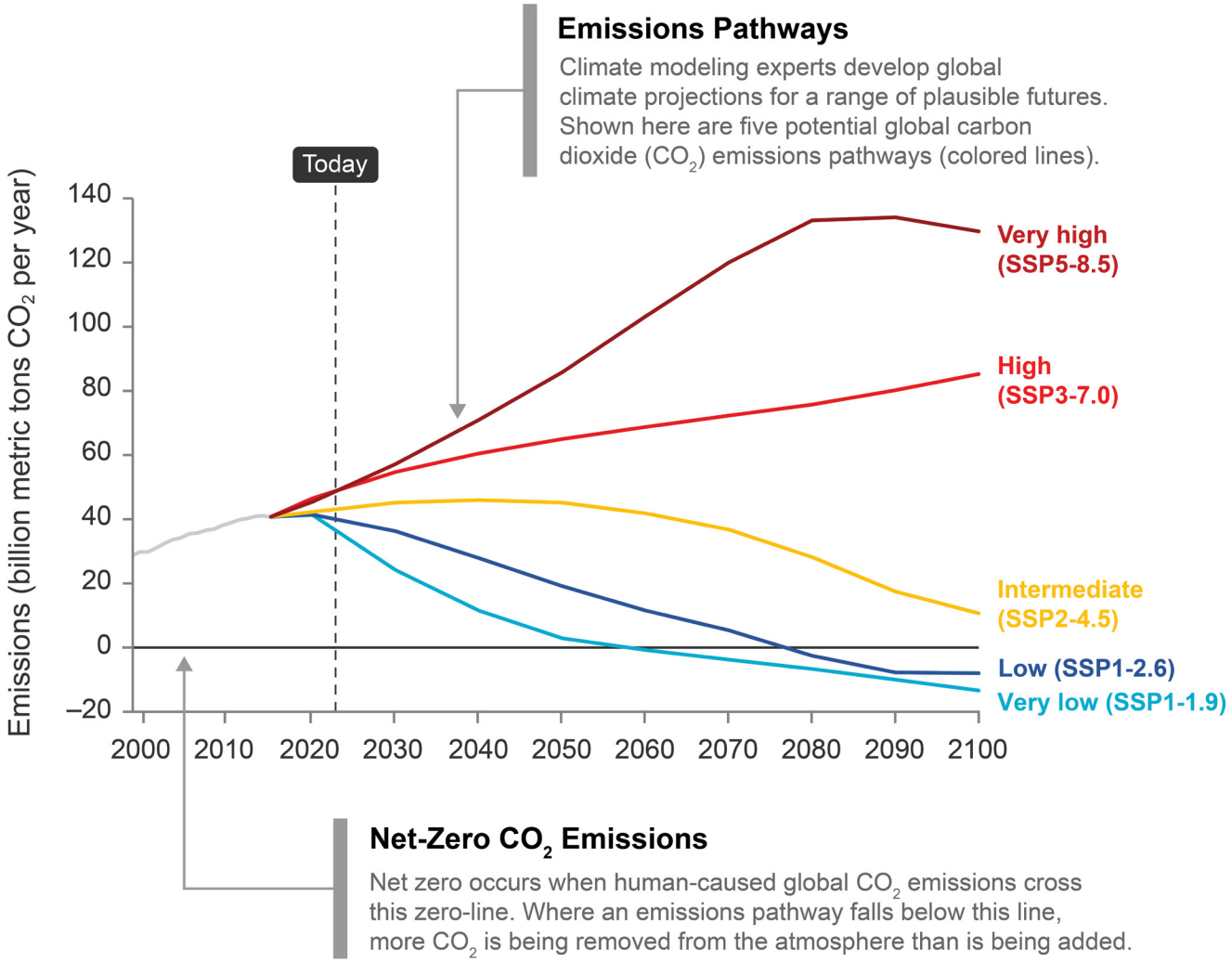
Once $CO_2$ emissions reach net zero, the global warming driven by $CO_2$ is expected to stop: additional warming over the next few centuries is not necessarily "locked in" after net $CO_2$ emissions fall to zero. However, global average temperatures are not expected to fall for centuries unless $CO_2$ emissions become net negative, which is when $CO_2$ removal from the atmosphere exceeds $CO_2$ emissions from human activities. Regardless of when or if further warming is avoided, some long-term responses to the temperature changes that have already occurred will continue. These responses include sea level rise, ice sheet losses, and associated disruptions to human health, social systems, and ecosystems. In addition, the ocean will continue to acidify after the world reaches net-zero $CO_2$ emissions, as it continues to gradually absorb $CO_2$ in the atmosphere from past emissions. {2.1, 2.3, 3.1; Ch. 2, Introduction}

National and international commitments seek to limit global warming to well below 2°C (3.6°F), and preferably to 1.5°C (2.7°F), compared to preindustrial temperature conditions (defined as the 1850–1900 average). To achieve this, global $CO_2$ emissions would have to reach net zero by around 2050 (Figure 1.4); global emissions of all greenhouse gases would then have to reach net zero within the following few decades. {2.3, 32.1}



Andrea Ruedy Trimble

## Future Global Carbon Dioxide Emissions Pathways




**Different scenarios of future carbon dioxide emissions are used to explore the range of possible climate futures.**

**Figure 1.4.** The five scenarios shown (colored lines) demonstrate potential global carbon dioxide ($CO_2$) emissions pathways modeled from 2015 through 2100, with the solid light gray line showing observed global $CO_2$ emissions from 2000 to 2015. See Table 3 in the Guide to the Report for scenario definitions. Many projected impacts described in this report are based on a potential climate future defined by one or more of these scenarios for future $CO_2$ emissions from human activities, the largest long-term driver of climate change. The vertical dashed line, labeled "Today," marks the year 2023; the solid horizontal black line marks net-zero $CO_2$ emissions. Adapted with permission from Figure TS.4 in Arias et al. 2021.

While US greenhouse gas emissions are falling, the current rate of decline is not sufficient to meet national and international climate commitments and goals. US net greenhouse gas emissions remain substantial and would have to decline by more than 6% per year on average, reaching net-zero emissions around midcentury, to meet current national mitigation targets and international temperature goals; by comparison, US greenhouse gas emissions decreased by less than 1% per year on average between 2005 and 2019. {32.1}

Many cost-effective options that are feasible now have the potential to substantially reduce emissions over the next decade. Faster and more widespread deployment of renewable energy and other zero- and low-carbon energy options can accelerate the transition to a decarbonized economy and increase the chances of meeting a 2050 national net-zero greenhouse gas emissions target for the US. However, to reach the US net-zero emissions target, additional mitigation options need to be explored and advanced (see "Available mitigation strategies can deliver substantial emissions reductions, but additional options are needed to reach net zero" below). {5.3, 6.3, 32.2, 32.3}

David Zeiset

# How the United States Is Experiencing Climate Change

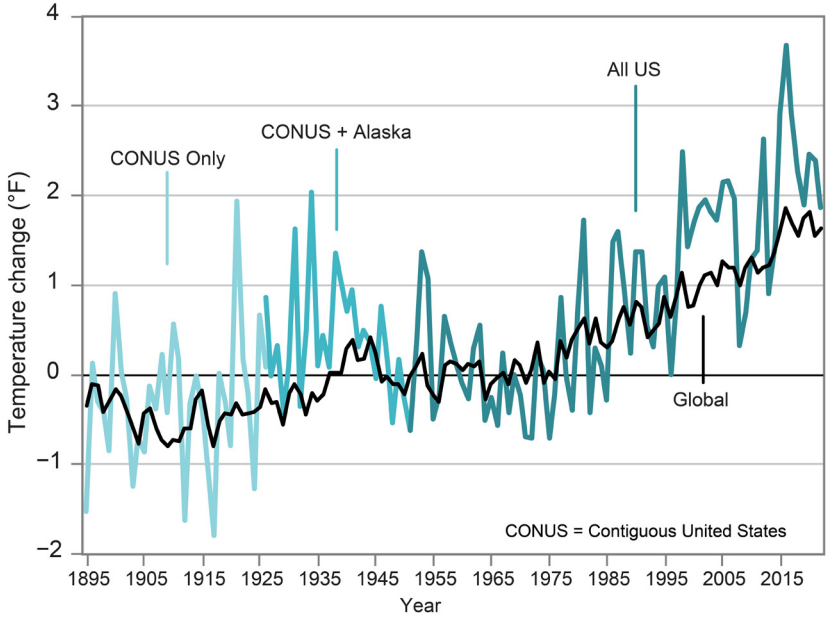
As extreme events and other climate hazards intensify, harmful impacts on people across the United States are increasing. Climate impacts—combined with other stressors—are leading to ripple effects across sectors and regions that multiply harms, with disproportionate effects on underserved and overburdened communities.

## Current climate changes are unprecedented over thousands of years

Global greenhouse gas emissions from human activities continue to increase, resulting in rapid warming (Figure 1.5) and other large-scale changes, including rising sea levels, melting ice, ocean warming and acidification, changing rainfall patterns, and shifts in timing of seasonal events. Many of the climate conditions and impacts people are experiencing today are unprecedented for thousands of years (Figure 1.6). {2.1, 3.1; Figures A4.6, A4.7, A4.10, A4.13}

As the world's climate has shifted toward warmer conditions, the frequency and intensity of extreme cold events have declined over much of the US, while the frequency, intensity, and duration of extreme heat have increased. Across all regions of the US, people are experiencing warming temperatures and longer-lasting heatwaves. Over much of the country, nighttime temperatures and winter temperatures have warmed more rapidly than daytime and summer temperatures. Many other extremes, including heavy precipitation, drought, flooding, wildfire, and hurricanes, are becoming more frequent and/or severe, with a cascade of effects in every part of the country. {2.1, 2.2, 3.4, 4.1, 4.2, 7.1, 9.1; Ch. 2, Introduction; App. 4; Focus on Compound Events}

### US and Global Changes in Average Surface Temperature




**The US has warmed rapidly since the 1970s.**

**Figure 1.5.** The graph shows the change in US annual average surface temperature during 1895–2022 compared to the 1951–1980 average. The temperature trend changes color as data become available for more regions of the US, with Alaska data added to the average temperature for the contiguous US (CONUS) beginning in 1926 (medium blue line) and Hawai'i, Puerto Rico, and US-Affiliated Pacific Islands data added beginning in 1951 (dark blue line). Global average surface temperature is shown by the black line. Figure credit: NOAA NCEI and CISESS NC.

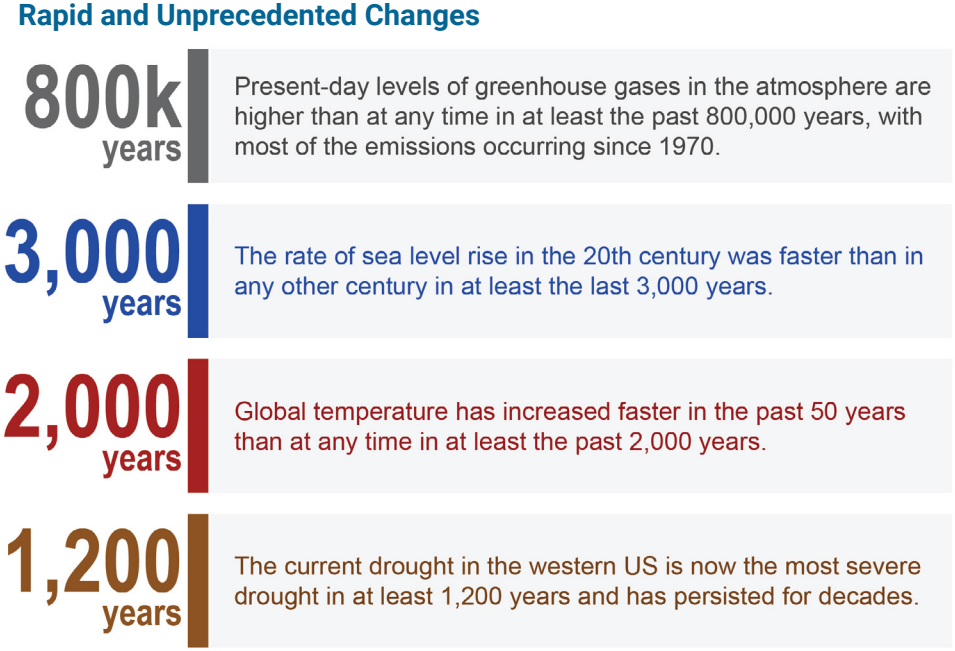



**Figure 1.6.** Human activities since industrialization have led to increases in atmospheric greenhouse gas concentrations that are unprecedented in records spanning hundreds of thousands of years. These are examples of some of the large and rapid changes in the climate system that are occurring as the planet warms. (Greenhouse gas concentrations {2.1}; sea level rise {3.4}; global temperature {2.1}; drought {2.2, 3.5}) Figure credit: USGCRP and ICF.

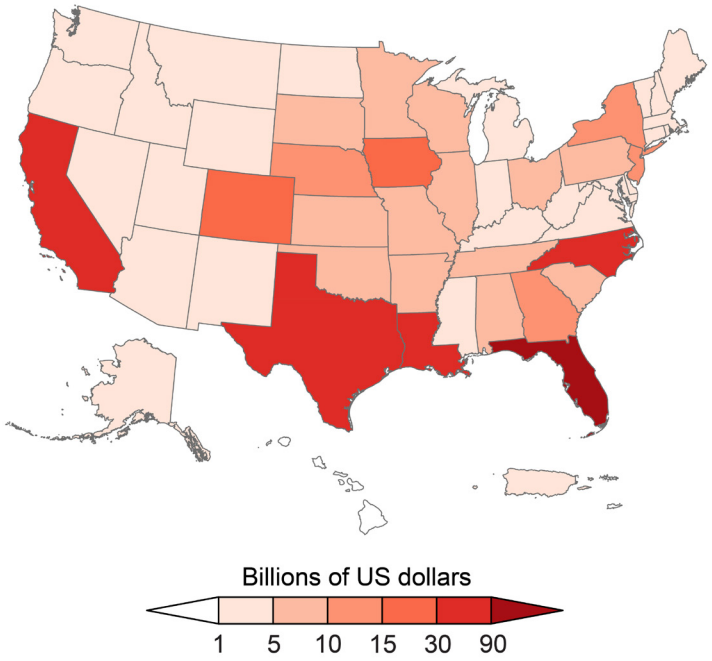
## Risks from extreme events are increasing

One of the most direct ways that people experience climate change is through changes in extreme events. Harmful impacts from more frequent and severe extremes are increasing across the country—including increases in heat-related illnesses and death, costlier storm damages, longer droughts that reduce agricultural productivity and strain water systems, and larger, more severe wildfires that threaten homes and degrade air quality. {2.2, 4.2, 12.2, 14.2, 15.1, 19.2; Focus on Western Wildfires}

Extreme weather events cause direct economic losses through infrastructure damage, disruptions in labor and public services, and losses in property values. The number and cost of weather-related disasters have increased dramatically over the past four decades, in part due to the increasing frequency and intensity of extreme events and in part due to increases in assets at risk (through population growth, rising property values, and continued development in hazard-prone areas). Low-income communities, communities of color, and Tribes and Indigenous Peoples experience high exposure and vulnerability to extreme events due to both their proximity to hazard-prone areas and lack of adequate infrastructure or disaster management resources. {2.2, 4.2, 17.3, 19.1; Focus on Compound Events}

In the 1980s, the country experienced, on average, one (inflation-adjusted) billion-dollar disaster every four months. Now, there is one every three weeks, on average. Between 2018 and 2022, the US experienced 89 billion-dollar events (Figure 1.7). Extreme events cost the US close to $150 billion each year—a conservative estimate that does not account for loss of life, healthcare-related costs, or damages to ecosystem services. {2.2, 19.1; Ch. 2, Introduction; Figures 4.1, A4.5}

**Damages by State from Billion-Dollar Disasters (2018–2022)**




**The US now experiences, on average, a billion-dollar weather or climate disaster every three weeks.**

**Figure 1.7.** Billion-dollar weather and climate disasters are events where damages/costs reach or exceed $1 billion, including adjustments for inflation. Between 2018 and 2022, 89 such events affected the US, including 4 droughts, 6 floods, 52 severe storms, 18 tropical cyclones, 5 wildfires, and 4 winter storm events (see Figure A4.5 for the number of billion-dollar disasters per year). During this period, Florida had the highest total damages ($140 billion) and experienced the highest damages from a single event—Hurricane Ian ($113 billion). Over the 1980–2022 period, Texas had the highest total damages ($375 billion). While similar data are not available for the US-Affiliated Pacific Islands, Super Typhoon Yutu caused $500 million in property damage alone in Saipan and the northern Marianas in 2018 (NCEI 2019). Increasing costs over time are driven by changes in the assets at risk and the increase in frequency or intensity of extreme events caused by climate change. Adapted from NCEI 2023.

## Cascading and compounding impacts increase risks

The impacts and risks of climate change unfold across interacting sectors and regions. For example, wildfire in one region can affect air quality and human health in other regions, depending on where winds transport smoke. Further, climate change impacts interact with other stressors, such as the COVID-19 pandemic, environmental degradation, or socioeconomic stressors like poverty and lack of adequate housing that disproportionately impact overburdened communities. These interactions and interdependencies can lead to cascading impacts and sudden failures. For example, climate-related shocks to the food supply chain have led to local to global impacts on food security and human migration patterns that affect US economic and national security interests. {11.3, 17.1, 17.2, 17.3, 18.1, 22.3, 23.4, 31.3; Introductions in Chs. 2, 17, 18; Focus on Compound Events; Focus on Risks to Supply Chains; Focus on COVID-19 and Climate Change}

The risk of two or more extreme events occurring simultaneously or in quick succession in the same region—known as compound events—is increasing. Climate change is also increasing the risk of multiple extremes occurring simultaneously in different locations that are connected by complex human and natural systems. For instance, simultaneous megafires across multiple western states and record back-to-back Atlantic hurricanes in 2020 caused unprecedented demand on federal emergency response resources. {2.2, 3.2, 15.1, 22.2, 26.4; Focus on Compound Events; Ch. 4, Introduction}

Compound events often have cascading impacts that cause greater harm than individual events. For example, in 2020, record-breaking heat and widespread drought contributed to concurrent destructive wildfires across California, Oregon, and Washington, exposing millions to health hazards and straining firefighting resources. Ongoing drought amplified the record-breaking Pacific Northwest heatwave of June 2021, which

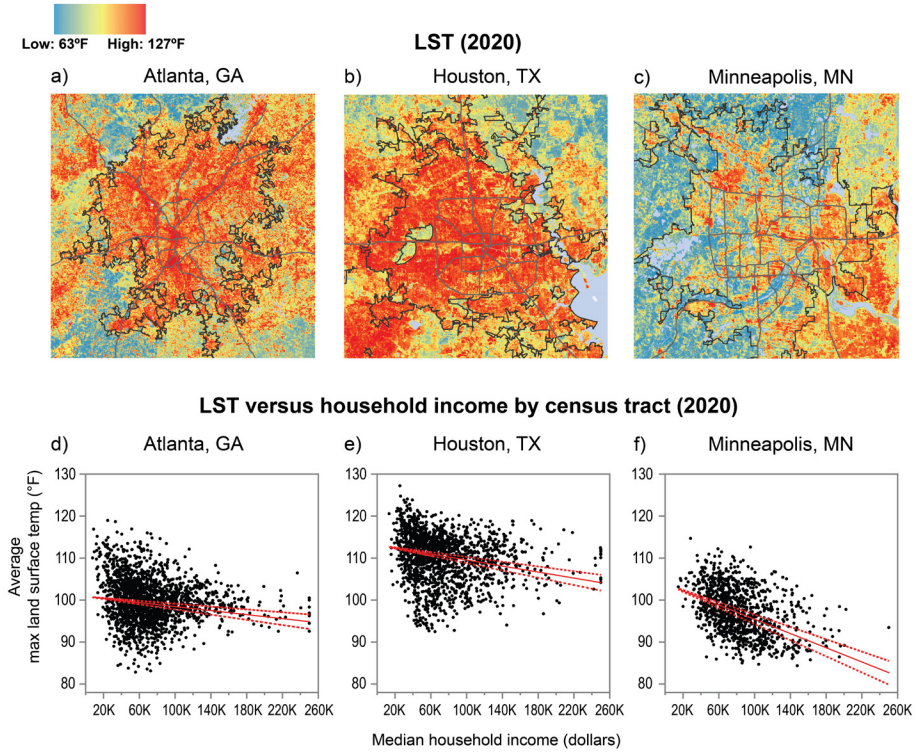
was made 2° to 4°F hotter by climate change. The heatwave led to more than 1,400 heat-related deaths, another severe wildfire season, mass die-offs of fishery species important to the region's economy and Indigenous communities, and total damages exceeding $38.5 billion (in 2022 dollars). {27.3; Ch. 2, Introduction; Focus on Compound Events, Focus on Western Wildfires}

## Climate change exacerbates inequities

Some communities are at higher risk of negative impacts from climate change due to social and economic inequities caused by ongoing systemic discrimination, exclusion, and under- or disinvestment. Many such communities are also already overburdened by the cumulative effects of adverse environmental, health, economic, or social conditions. Climate change worsens these long-standing inequities, contributing to persistent disparities in the resources needed to prepare for, respond to, and recover from climate impacts. {4.2, 9.2, 12.2, 14.3, 15.2, 16.1, 16.2, 18.2, 19.1, 20.1, 20.3, 21.3, 22.1, 23.1, 26.4, 27.1, 31.2}

For example, low-income communities and communities of color often lack access to adequate flood infrastructure, green spaces, safe housing, and other resources that help protect people from climate impacts. In some areas, patterns of urban growth have led to the displacement of under-resourced communities to suburban and rural areas with less access to climate-ready housing and infrastructure. Extreme heat can lead to higher rates of illness and death in low-income neighborhoods, which are hotter on average (Figure 1.8). Neighborhoods that are home to racial minorities and low-income people have the highest inland (riverine) flood exposures in the South, and Black communities nationwide are expected to bear a disproportionate share of future flood damages—both coastal and inland (Figure 1.9). {4.2, 11.3, 12.2, 15.1, 22.1, 22.2, 26.4, 27.1; Ch. 2, Introduction}

### Land Surface Temperature and Its Relationship to Median Household Income for Three Cities

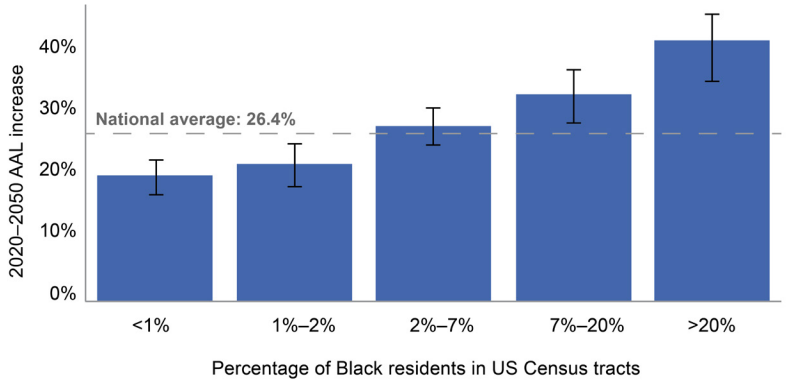



**Lower-income urban neighborhoods experience higher surface temperatures.**

**Figure 1.8.** The figure shows the spatial distribution of maximum land surface temperature (LST) in 2020 for Atlanta (**a**), Houston (**b**), and Minneapolis (**c**). Graphs (**d**), (**e**), and (**f**) depict the relationship between maximum LST and median household income across census tracts in each city (see also Figure A4.4). A statistical trend analysis (the Theil-Sen estimator) returns negative values for all three cities, indicating that LST decreases as income increases (solid red line). Dashed red lines indicate the 95% confidence interval, meaning that the true slope of the trend is expected to fall within this range. Note that LST is measured at ground level and may differ from surface air temperature, which is measured at a height of 2 meters. {Figure 12.6} Portions of this figure include intellectual property of Esri and its licensors and are used under license. Copyright © 2020 Esri and its licensors. All rights reserved. Figure credit: University of California, Davis; University of Texas at El Paso; Massachusetts Institute of Technology; City of Phoenix, Arizona; and USGS.

These disproportionate impacts are partly due to exclusionary housing practices—both past and ongoing—that leave underserved communities with less access to heat and flood risk-reduction strategies and other economic, health, and social resources. For example, areas that were historically redlined—a practice in which lenders avoided providing services to communities, often based on their racial or ethnic makeup—continue to be deprived of equitable access to environmental amenities like urban green spaces that reduce exposure to climate impacts. These neighborhoods can be as much as 12°F hotter during a heatwave than nearby wealthier neighborhoods. {8.3, 9.2, 12.2, 15.2, 20.3, 21.3, 22.1, 26.4, 27.1, 32.4; Ch. 2, Introduction}

### Projected Increases in Average Annual Losses (AALs) from Floods by 2050




**Losses due to floods are projected to increase disproportionately in US Census tracts with higher percentages of Black residents.**

**Figure 1.9.** The bars show that the average annual losses—or the economic damage in a typical year—due to floods in census tracts with a Black population of at least 20% are projected to increase at roughly twice the rate of that in tracts where Black populations make up less than 1% of population. {Figure 4.14} Adapted from Wing et al. 2022 [CC BY 4.0].

## Harmful impacts will increase in the near term

Even if greenhouse gas emissions fall substantially, the impacts of climate change will continue to intensify over the next decade (see "Meeting US mitigation targets means reaching net-zero emissions" above; Box 1.4), and all US regions are already experiencing increasingly harmful impacts. Although a few US regions or sectors may experience limited or short-term benefits from climate change, adverse impacts already far outweigh any positive effects and will increasingly eclipse benefits with additional warming. {2.3, 19.1; Ch. 2, Introduction; Chs. 21–30}

Table 1.2 shows examples of critical impacts expected to affect people in each region between now and 2030, with disproportionate effects on overburdened communities. While these examples affect particular regions in the near term, impacts often cascade through social and ecological systems and across borders and may lead to longer-term losses. {15.2, 18.2, 20.1; Figure 15.5; Ch. 20, Introduction}

## Table 1.2. Climate Change Is Already Affecting All US Regions and Will Continue to Have Impacts in the Near Term

The table shows three climate impacts of significant concern to each US region between now and 2030. Icons indicate general categories of impacts: infrastructure, water supply, health and well-being, food security, economy, livelihoods and heritage, and ecosystems. More information can be found in the regional chapters (Chs. 21–30).

Infrastructure | Water Supply | Health and Well-Being | Food Security | Economy | Livelihoods and Heritage | Ecosystems

### Northeast

- Extreme weather events damage critical infrastructure. {21.1}
- Warming temperatures shift distributions of coastal and marine species and habitats. {21.2}
- Extreme heat and flooding disproportionately impact overburdened communities. {21.3}

### Southeast

- Sea level rise and coastal flooding harm rapidly growing communities. {22.1}
- Extreme heat threatens human health, especially stressing urban communities. {22.2}
- Heavy rain and longer dry spells reduce water supply and access. {22.4}

### US Caribbean

- Agricultural losses, especially from tropical cyclones, threaten food security. {23.1}
- Severe drought leads to large agricultural and economic losses. {23.3}
- Rising temperatures increase mortality and power demand; hurricanes and storms stress power grids. {23.2, 23.4}

### Midwest

- Rising temperatures and extreme events threaten livelihoods and trades. {24.2}
- Extreme weather events harm public health. {24.3}
- Rising temperatures and extreme rainfall damage buildings, homes, and businesses. {24.4}

### Northern Great Plains

- Rising temperatures and decreasing snowpack reduce water supply. {25.1}
- Increases in extreme heat, wildfire, and flooding harm physical and mental health. {25.1, 25.2}
- Livelihoods are at greater risk, especially in agriculture, recreation, and energy sectors. {25.3}

### Southern Great Plains

- Drier conditions threaten agriculture, ecosystems, and water supplies. {26.1, 26.2, 26.5}
- Extreme heat and high humidity harm human health and exacerbate inequities. {26.4}
- Multiple stressors and extreme events disrupt business, outdoor recreation, and leisure activities. {26.1, 26.2, 26.3}

## Northwest

Less water is available for hydropower, rural communities, and aquatic ecosystems. {27.1, 27.2, 27.4}

Extreme heat and wildfire smoke endanger at-risk urban, rural, and Tribal communities. {27.1, 27.3, 27.5}

Wildfire, extreme heat, and floods threaten livelihoods and heritage tied to natural resources. {27.1, 27.3, 27.6}

## Alaska

Landscape degradation increases damage to private and municipal infrastructure. {29.2, 29.4}

Reduced fish stocks harm local economies, Tribal sovereignty, and overall well-being. {29.6, 29.7}

Diminished access to mammals, seabirds, fish, and vegetation decreases local food security. {29.5}

## Southwest

Intensifying drought and decreases in groundwater recharge reduce water supply. {28.1}

Economic losses to farmers and ranchers increase. {28.3}

Extreme heat, drought, wildfire smoke, and coastal flooding harm physical and mental health. {28.3, 28.4}

## Hawai‘i and US-Affiliated Pacific Islands

Sea level rise and saltwater intrusion reduce irrigation and drinking water supply. {30.1}

Damages to the coastal built environment, including traditional structures, increase. {30.3, 30.5}

Risks to unique and biodiverse flora and fauna continue to grow. {30.4}

# Current and Future Climate Risks to the United States

Climate changes are making it harder to maintain safe homes and healthy families; reliable public services; a sustainable economy; thriving ecosystems, cultures, and traditions; and strong communities. Many of the extreme events and harmful impacts that people are already experiencing will worsen as warming increases and new risks emerge.

## Safe, reliable water supplies are threatened by flooding, drought, and sea level rise

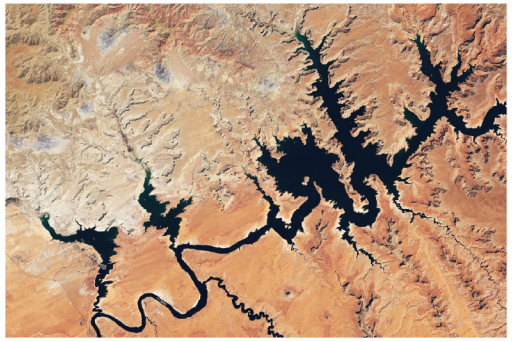
More frequent and intense heavy precipitation events are already evident, particularly in the Northeast and Midwest. Urban and agricultural environments are especially vulnerable to runoff and flooding. Between 1981 and 2016, US corn yield losses from flooding were comparable to those from extreme drought. Runoff and flooding also transport debris and contaminants that cause harmful algal blooms and pollute drinking water supplies. Communities of color and low-income communities face disproportionate flood risks. {2.2, 4.2, 6.1, 9.2, 21.3, 24.1, 24.5, 26.4; Figure A4.8}

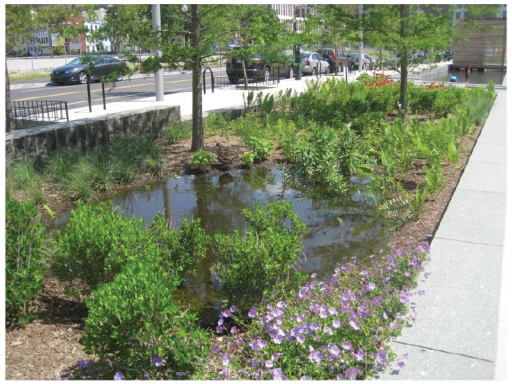
Between 1980 and 2022, drought and related heatwaves caused approximately $328 billion in damages (in 2022 dollars). Recent droughts have strained surface water and groundwater supplies, reduced agricultural productivity, and lowered water levels in major reservoirs, threatening hydropower generation. As higher temperatures increase irrigation demand, increased pumping could endanger groundwater supplies, which are already declining in many major aquifers. {4.1, 4.2; Figure A4.9}

Droughts are projected to increase in intensity, duration, and frequency, especially in the Southwest, with implications for surface water and groundwater supplies. Human and natural systems are threatened by rapid shifts between wet and dry periods that make water resources difficult to predict and manage. {2.2, 2.3, 4.1, 4.2, 5.1, 28.1}

In coastal environments, dry conditions, sea level rise, and saltwater intrusion endanger groundwater aquifers and stress aquatic ecosystems. Inland, decreasing snowpack alters the volume and timing of streamflow and increases wildfire risk. Small rural water providers that often depend on a single water source or have limited capacity are especially vulnerable. {4.2, 7.2, 9.2, 21.2, 22.1, 23.1, 23.3, 25.1, 27.4, 28.1, 28.2, 28.5, 30.1; Figure A4.7}

Many options are available to protect water supplies, including reservoir optimization, nature-based solutions, and municipal management systems to conserve and reuse water. Collaboration on flood hazard management at regional scales is particularly important in areas where flood risk is increasing, as cooperation can provide solutions unavailable at local scales. {4.3, 9.3, 26.5; Focus on Blue Carbon}





(**left**; Toledo, Ohio) Rising temperatures are intensifying harmful algal blooms, negatively affecting human and animal health. (**top right**; Utah, Arizona) Water levels on Lake Powell have fallen to historic lows in recent years, affecting millions of people across the Southwest. (**bottom right**) Rain gardens, a form of green infrastructure, absorb excess stormwater. Photo credits: (left) Aerial Associates Photography Inc. by Zachary Haslick; (top right) NASA Earth Observatory images by Lauren Dauphin, using Landsat data from the USGS; (bottom right) Alisha Goldstein, EPA.

## Disruptions to food systems are expected to increase

As the climate changes, increased instabilities in US and global food production and distribution systems are projected to make food less available and more expensive. These price increases and disruptions are expected to disproportionately affect the nutrition and health of women, children, older adults, and low-wealth communities. {11.2, 15.2}

Climate change also disproportionately harms the livelihoods and health of communities that depend on agriculture, fishing, and subsistence lifestyles, including Indigenous Peoples reliant on traditional food sources. Heat-related stress and death are significantly greater for farmworkers than for all US civilian workers. {11.2, 11.3, 15.1, 15.2, 16.1; Focus on Risks to Supply Chains}

While farmers, ranchers, and fishers have always faced unpredictable weather, climate change heightens risks in many ways:

- Increasing temperatures, along with changes in precipitation, reduce productivity, yield, and nutritional content of many crops. These changes can introduce disease, disrupt pollination, and result in crop failure, outweighing potential benefits of longer growing seasons and increased $CO_2$ fertilization. {11.1, 19.1, 21.1, 22.4, 23.3, 24.1, 26.2}
- Heavy rain and more frequent storms damage crops and property and contaminate water supplies. Longer-lasting droughts and larger wildfires reduce forage production and nutritional quality, diminish water supplies, and increase heat stress on livestock. {23.2, 25.3, 28.3}
- Increasing water temperatures, invasive aquatic species, harmful algal blooms, and ocean acidification and deoxygenation put fisheries at risk. Fishery collapses can result in large economic losses, as well as loss of cultural identity and ways of life. {11.3, 29.3}

In response, some farmers and ranchers are adopting innovations—such as agroecological practices, data-driven precision agriculture, and carbon monitoring—to improve resilience, enhance soil carbon storage, and reduce emissions. Across the Nation, Indigenous food security efforts are helping improve community resilience to climate change while also improving cultural resilience. Some types of aquaculture have the potential to increase climate-smart protein production, human nutrition, and food security, although some communities have raised concerns over issues such as conflict with traditional livelihoods and the introduction of disease or pollution. {10.2, 11.1, 29.6, 25.5; Boxes 22.3, 27.2}

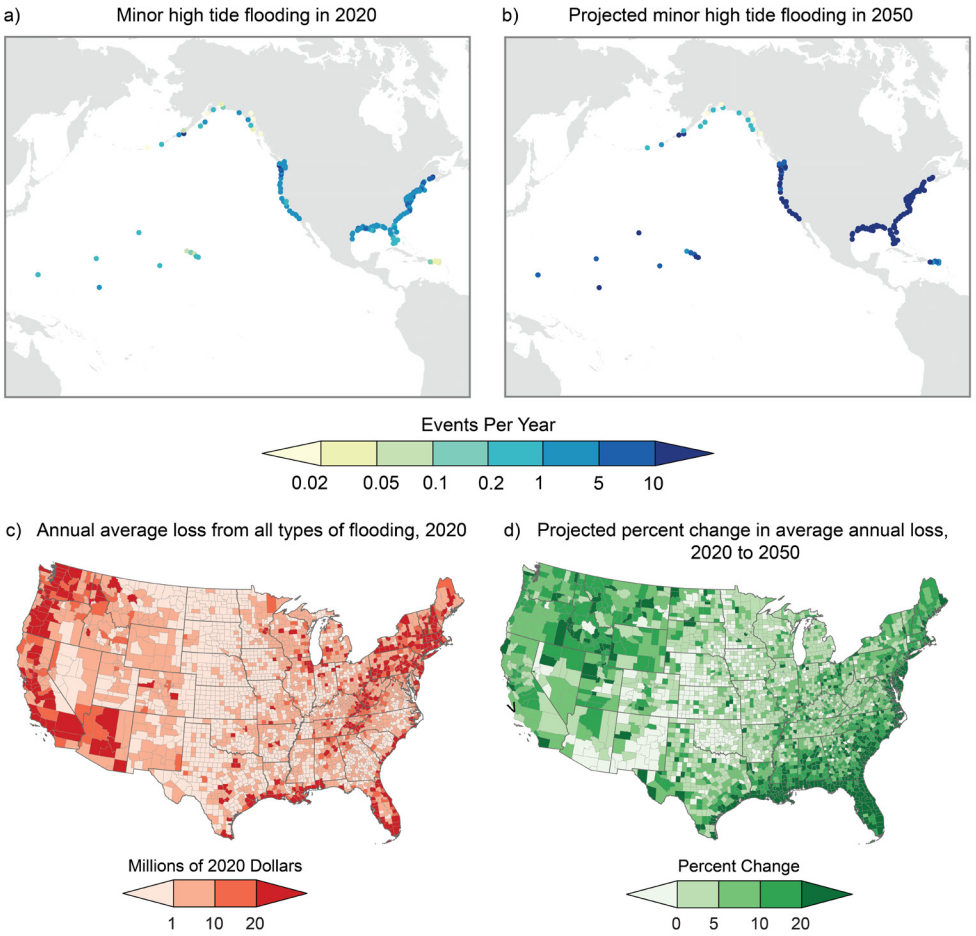
(**left**; Baltimore, Maryland) Urban farms offer the potential to reduce carbon emissions while helping to improve community food security. (**top right**; California) A Northern California vineyard is affected by wildfire. (**bottom right**; Kenai River, Alaska) Recent climate extremes have contributed to declines in many salmon populations. Photo credits: (left) Preston Keres, USDA/FPAC; (top right) Ordinary Mario/iStock via Getty Images; (bottom right) Eric Vance, EPA.

## Homes and property are at risk from sea level rise and more intense extreme events

Homes, property, and critical infrastructure are increasingly exposed to more frequent and intense extreme events, increasing the cost of maintaining a safe and healthy place to live. Development in fire-prone areas and increases in area burned by wildfires have heightened risks of loss of life and property damage in many areas across the US. Coastal communities across the country—home to 123 million people (40% of the total US population)—are exposed to sea level rise (Figure 1.10), with millions of people at risk of being displaced from their homes by the end of the century. {2.3, 9.1, 12.2, 22.1, 27.4, 30.3; Figures A4.10, A4.14; Focus on Western Wildfires}

People who regularly struggle to afford energy bills—such as rural, low-income, and older fixed-income households and communities of color—are especially vulnerable to more intense extreme heat events and associated health risks, particularly if they live in homes with poor insulation and inefficient cooling systems. For example, Black Americans are more likely to live in older, less energy efficient homes and face disproportionate heat-related health risks. {5.2, 15.2, 15.3, 22.2, 26.4, 32.4; Figure A4.4}

Accessible public cooling centers can help protect people who lack adequate air-conditioning on hot days. Strategic land-use planning in cities, urban greenery, climate-smart building codes, and early warning communication can also help neighborhoods adapt. However, other options at the household scale, such as hardening homes against weather extremes or relocation, may be out of reach for renters and low-income households without assistance. {12.3, 15.3, 19.3, 22.2}




## US Flooding Risks in 2020 and 2050

### Increasing flooding puts more people and assets at risk.

**Figure 1.10.** (**top row**) Maps show (**a**) the average number of minor high tide flooding events per year in 2020 (with historical sea level rise) and (**b**) the expected number of events per year in 2050 (when driven by extrapolated sea level rise). (**bottom row**) Maps show (**c**) average annual loss (AAL) from all types of flooding in millions of dollars in 2020 and (**d**) the projected changes in AAL in 2050 relative to 2020. AAL estimates were made only for the contiguous US. Over the next three decades, the number of flooding days along all coastlines of the US is expected to increase. These increases in the occurrence of flooding will drive greater AALs, especially in coastal areas of the US. (a, b) Adapted from Sweet et al. 2022; (c, d) adapted from Wing et al. 2022 [CC BY 4.0].

## Box 1.2. Migration and Displacement

Extreme events, such as extended drought, wildfire, and major hurricanes, have contributed to human migration and displacement. For example, numerous extreme events over the last two decades drove migration of vulnerable communities in Puerto Rico and the US Virgin Islands to the mainland. {9.2, 15.1, 17.2, 19.2, 23.1, 23.5; Box 18.2}

In the future, the combination of climate change and other factors, such as housing affordability, is expected to increasingly affect migration patterns. More severe wildfires in California, increasing sea level rise in Florida, and more frequent flooding in Texas are expected to displace millions of people. Climate-driven economic changes abroad, including reductions in crop yields, are expected to increase the rate of emigration to the United States. {9.2, 17.2, 19.2, 30.3}

From Alaska to low-lying Pacific atolls, forced migrations and displacements driven by climate change disrupt social networks, decrease housing security, and exacerbate grief, anxiety, and negative mental health outcomes. Indigenous Peoples, who have long faced land dispossession due to settler colonialism, are again being confronted with displacement and loss of traditional resources and practices. {4.2, 15.1, 16.1, 19.1, 20.1, 20.3, 22.1, 22.2, 29.1, 30.3; Box 18.2}

(**left**; Cedar Rapids, Iowa) More frequent and intense heavy precipitation events are already evident, particularly in the Northeast and Midwest. (**right**; Arizona) The 2021 Telegraph Fire destroyed homes and property. Photo credits: (left) Don Becker, USGS; (right) Andrew Avitt, USDA Forest Service.

## Infrastructure and services are increasingly damaged and disrupted by extreme weather and sea level rise

Climate change threatens vital infrastructure that moves people and goods, powers homes and businesses, and delivers public services. Many infrastructure systems across the country are at the end of their intended useful life and are not designed to cope with additional stress from climate change. For example, extreme heat causes railways to buckle, severe storms overload drainage systems, and wildfires result in roadway obstruction and debris flows. Risks to energy, water, healthcare, transportation, telecommunications, and waste management systems will continue to rise with further climate change, with many infrastructure systems at risk of failing. {12.2, 13.1, 15.2, 23.4, 26.5; Focus on Risks to Supply Chains}

In coastal areas, sea level rise threatens permanent inundation of infrastructure, including roadways, railways, ports, tunnels, and bridges; water treatment facilities and power plants; and hospitals, schools, and military bases. More intense storms also disrupt critical services like access to medical care, as seen after Hurricanes Irma and Maria in the US Virgin Islands and Puerto Rico. {9.2, 23.1, 28.2, 30.3}

At the same time, climate change is expected to place multiple demands on infrastructure and public services. For example, higher temperatures and other effects of climate change, such as greater exposure to stormwater or wastewater, will increase demand for healthcare. Continued increases in average temperatures and more intense heatwaves will heighten electricity and water demand, while wetter storms and intensified

hurricanes will strain wastewater and stormwater management systems. In the Midwest and other regions, aging energy grids are expected to be strained by disruptions and transmission efficiency losses from climate change. {23.4, 24.4, 30.2}

Forward-looking designs of infrastructure and services can help build resilience to climate change, offset costs from future damage to transportation and electrical systems, and provide other benefits, including meeting evolving standards to protect public health, safety, and welfare. Mitigation and adaptation activities are advancing from planning stages to deployment in many areas, including improved grid design and workforce training for electrification, building upgrades, and land-use choices. Grid managers are gaining experience planning and operating electricity systems with growing shares of renewable generation and working toward understanding the best approaches for dealing with the natural variability of wind and solar sources alongside increases in electrification. {5.3, 12.3, 13.1, 13.2, 22.3, 24.4, 32.3; Figure 22.17}

## Climate change exacerbates existing health challenges and creates new ones

Climate change is already harming human health across the US, and impacts are expected to worsen with continued warming. Climate change harms individuals and communities by exposing them to a range of compounding health hazards, including the following:

- More severe and frequent extreme events {2.2, 2.3, 15.1}
- Wider distribution of infectious and vector-borne pathogens {15.1, 26.1; Figure A4.16}
- Air quality worsened by smog, wildfire smoke, dust, and increased pollen {14.1, 14.2, 14.4, 23.1, 26.1}
- Threats to food and water security {11.2, 15.1}
- Mental and spiritual health stressors {15.1}

(**left**; Oregon) The Hooskanaden Landslide, triggered by heavy rainfall, caused substantial road damage. (**right**; Maunabo, Puerto Rico) Punta Tuna Wetlands Nature Reserve, which helps buffer the coastline from extreme events, was severely damaged during Hurricane Maria in 2017. Photo credits: (left) Oregon Department of Transportation [CC BY 2.0]; (right) Kenneth Wilsey, FEMA.

While climate change can harm everyone's health, its impacts exacerbate long-standing disparities that result in inequitable health outcomes for historically marginalized people, including people of color, Indigenous Peoples, low-income communities, and sexual and gender minorities, as well as older adults, people with disabilities or chronic diseases, outdoor workers, and children. {14.3, 15.2}

The disproportionate health impacts of climate change compound with similar disparities in other health contexts. For example, climate-related disasters during the COVID-19 pandemic, such as drought along the Colorado River basin, western wildfires, and Hurricane Laura, disproportionately magnified COVID-19 exposure, transmission, and disease severity and contributed to worsened health conditions for essential workers, older adults, farmworkers, low-wealth communities, and communities of color. {15.2; Focus on COVID-19 and Climate Change}

Large reductions in greenhouse gas emissions are expected to result in widespread health benefits and avoided death or illness that far outweigh the costs of mitigation actions. Improving early warning, surveillance, and communication of health threats; strengthening the resilience of healthcare systems; and supporting community-driven adaptation strategies can reduce inequities in the resources and capabilities needed to adapt as health threats from climate change continue to grow. {14.5, 15.3, 26.1, 30.2, 32.4}

(**left**; New York, New York) The Empire State Building is shrouded in a haze caused by smoke from the 2023 Canadian wildfires. (top right; Charleston, South Carolina) An ambulance drives through floodwaters. (bottom right; Atlanta, Georgia) Heatwaves in the Southeast are happening more frequently. Park amenities, such as trees and splash pads, help cool people on hot days. Photo credits: (left) Anthony Quintano [CC BY 2.0]; (top right) US Air National Guard photo by Tech. Sgt. Jorge Intriago; (bottom right) ucumari photography [CC BY-NC-ND 2.0]

## Box 1.3. Indigenous Ways of Life and Spiritual Health

Indigenous communities, whose ways of life, cultures, intergenerational continuity, and spiritual health are tied to nature and the environment, are experiencing disproportionate health impacts of climate change. Rising temperatures and intensifying extreme events are reducing biodiversity and shifting the ranges of culturally important species like Pacific salmon, wild rice, and moose, making it more difficult for Indigenous Peoples to fish, hunt, and gather traditional and subsistence resources within Tribal jurisdictions. Heatwaves can prevent Tribal members from participating in traditional ceremonies, while flooding, erosion, landslides, and wildfires increasingly disrupt or damage burial grounds and ceremonial sites. {16.1, 15.2, 27.6}

Indigenous Peoples are leading numerous actions in response to climate change, including planning and policy initiatives, youth movements, cross-community collaborative efforts, and the expansion of renewable energy (Figure 1.11). Many of these efforts involve planning processes that start with place-based Indigenous Knowledge of local climate and ecosystems. {16.3}

### Exemplifying Indigenous Resilience

**Figure 1.11.** For over 2,000 years, the Hopi People have farmed on land with only 6–10 inches of annual precipitation. Today, Hopi children learn both the practices and process of Hopi dryland farming and the values, customs, and identities that underpin them. Photo credit: ©Michael K. Johnson. {Panel from Figure 16.6}

## Ecosystems are undergoing transformational changes

Together with other stressors, climate change is harming the health and resilience of ecosystems, leading to reductions in biodiversity and ecosystem services. Increasing temperatures continue to shift habitat ranges as species expand into new regions or disappear from unfavorable areas, altering where people can hunt, catch, or gather economically important and traditional food sources. Degradation and extinction of local flora and fauna in vulnerable ecosystems like coral reefs and montane rainforests are expected in the near term, especially where climate changes favor invasive species or increase susceptibility to pests and pathogens. Without significant emissions reductions, rapid shifts in environmental conditions are expected to lead to irreversible ecological transformations by mid- to late century. {2.3, 6.2, 7.1, 7.2, 8.1, 8.2, 10.1, 10.2, 21.1, 24.2, 27.2, 28.5, 29.3, 29.5, 30.4; Figure A4.12}

Changes in ocean conditions and extreme events are already transforming coastal, aquatic, and marine ecosystems. Coral reefs are being lost due to warming and ocean acidification, harming important fisheries; coastal forests are converting to ghost forests, shrublands, and marsh due to sea level rise, reducing coastal protection; lake and stream habitats are being degraded by warming, heavy rainfall, and invasive species, leading to declines in economically important species. {8.1. 10.1, 21.2, 23.2, 24.2, 27.2; Figures 8.7, A4.11}

Increased risks to ecosystems are expected with further climate change and other environmental changes, such as habitat fragmentation, pollution, and overfishing. For example, mass fish die-offs from extreme summertime heat are projected to double by midcentury in northern temperate lakes under a very high scenario (RCP8.5). Continued climate changes are projected to exacerbate runoff and erosion, promote harmful algal blooms, and expand the range of invasive species. {4.2, 7.1, 8.2, 10.1, 21.2, 23.2, 24.2, 27.2, 28.2, 30.4}

While adaptation options to protect fragile ecosystems may be limited, particularly under higher levels of warming, management and restoration measures can reduce stress on ecological systems and build resilience. These measures include migration assistance for vulnerable species and protection of essential habitats, such as establishing wildlife corridors or places where species can avoid heat. Opportunities for nature-based solutions that assist in mitigation exist across the US, particularly those focused on protecting existing carbon sinks and increasing carbon storage by natural ecosystems. {8.3, 10.3, 23.2, 27.2; Focus on Blue Carbon}

(**top left**; Nags Head Woods, North Carolina) Coastal ghost forests result when trees are killed by sea level rise and saltwater intrusion. (**top right**; Molokai Island, Hawai'i) High island ecosystems are at risk due to invasive species, habitat destruction, intensifying fire, and drought. (**bottom**; Florida) A diver works on coral reef restoration around Florida Keys National Marine Sanctuary. Photo credits: (top left) NC Wetlands [CC BY 2.0]; (top right) Lucas Fortini, USGS; (bottom) Mitchell Tartt, NOAA.

## Climate change slows economic growth, while climate action presents opportunities

With every additional increment of global warming, costly damages are expected to accelerate. For example, 2°F of warming is projected to cause more than twice the economic harm induced by 1°F of warming. Damages from additional warming pose significant risks to the US economy at multiple scales and can compound to dampen economic growth. {19.1}

- International impacts can disrupt trade, amplify costs along global supply chains, and affect domestic markets. {17.3, 19.2; Focus on Risks to Supply Chains}
- While some economic impacts of climate change are already being felt across the country, the impacts of future changes are projected to be more significant and apparent across the US economy. {19.1}
- States, cities, and municipalities confront climate-driven pressures on public budgets and borrowing costs amid spending increases on healthcare and disaster relief. {19.2}
- Household consumers face higher costs for goods and services, like groceries and health insurance premiums, as prices change to reflect both current and projected climate-related damages. {19.2}

Mitigation and adaptation actions present economic opportunities. Public and private measures—such as climate financial risk disclosures, carbon offset credit markets, and investments in green bonds—can avoid economic losses and improve property values, resilience, and equity. However, climate responses are not without risk. As innovation and trade open further investment opportunities in renewable energy and the country continues to transition away from fossil fuels, loss and disposal costs of stranded capital assets such as coal mines, oil and gas wells, and outdated power plants are expected. Climate solutions designed without input from affected communities can also result in increased vulnerability and cost burden. {17.3, 19.2, 19.3, 20.2, 20.3, 27.1, 31.6}

## Many regional economies and livelihoods are threatened by damages to natural resources and intensifying extremes

Climate change is projected to reduce US economic output and labor productivity across many sectors, with effects differing based on local climate and the industries unique to each region. Climate-driven damages to local economies especially disrupt heritage industries (e.g., fishing traditions, trades passed down over generations, and cultural heritage–based tourism) and communities whose livelihoods depend on natural resources. {11.3, 19.1, 19.3}

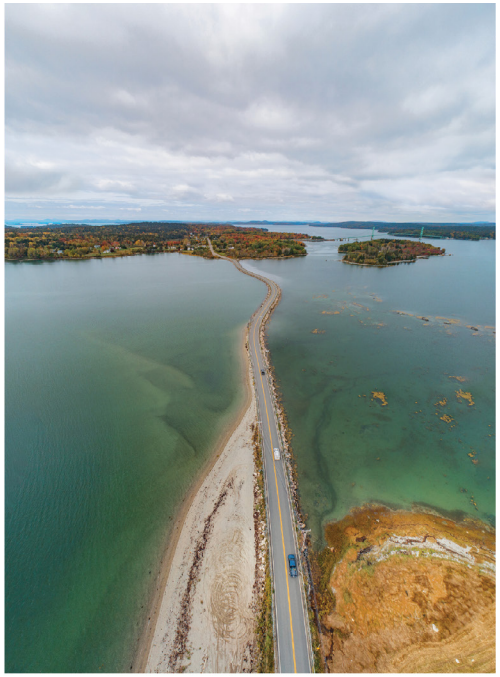
- As fish stocks in the Northeast move northward and to deeper waters in response to rapidly rising ocean temperatures, important fisheries like scallops, shrimp, and cod are at risk. In Alaska, climate change has already played a role in 18 major fishery disasters that were especially damaging for coastal Indigenous Peoples, subsistence fishers, and rural communities. {10.2, 21.2, 29.3}
- While the Southeast and US Caribbean face high costs from projected labor losses and heat health risks to outdoor workers, small businesses are already confronting higher costs of goods and services and potential closures as they struggle to recover from the effects of compounding extreme weather events. {22.3, 23.1}
- Agricultural losses in the Midwest, including lower corn yields and damages to specialty crops like apples, are linked to rapid shifts between wet and dry conditions and stresses from climate-induced increases in pests and pathogens. Extreme heat and more intense wildfire and drought in the Southwest are already threatening agricultural worker health, reducing cattle production, and damaging wineries. {24.1, 28.5}
- In the Northern Great Plains, agriculture and recreation are expected to see primarily negative effects related to changing temperature and rainfall patterns. By 2070, the

Southern Great Plains is expected to lose cropland acreage as lands transition to pasture or grassland. {25.3, 26.2}

- Outdoor-dependent industries, such as tourism in Hawai'i and the US-Affiliated Pacific Islands and skiing in the Northwest, face significant economic loss from projected rises in park closures and reductions in workforce as continued warming leads to deterioration of coastal ecosystems and shorter winter seasons with less snowfall. {7.2, 8.3, 10.1, 10.3, 19.1, 27.3, 30.4}

Mitigation and adaptation actions taken by businesses and industries promote resilience and offer long-term benefits to employers, employees, and surrounding communities. For example, as commercial fisheries adapt, diversifying harvest and livelihoods can help stabilize income or buffer risk. In addition, regulators and investors are increasingly requiring businesses to disclose climate risks and management strategies. {10.2, 19.3, 26.2}

Scarlett W.



(**top left**; Fort Myers Beach, Florida) Shops and restaurants were severely damaged or completed destroyed by Hurricane Ian in 2022. (**bottom left**; Whatcom County, Washington) Snow-based recreational industries, such as skiing in the Pacific Northwest, are projected to lose revenue due to declining snowpack. (**right**; Maine) A causeway connecting Little Deer Isle to Deer Isle (the largest lobster port in the state) is threatened by sea level rise. Photo credits: (top left) Coast Guard Petty Officer 3rd Class Gabriel Wisdom; (bottom left) US Forest Service–Pacific Northwest Region; (right) ©Jack Sullivan, Island Institute.

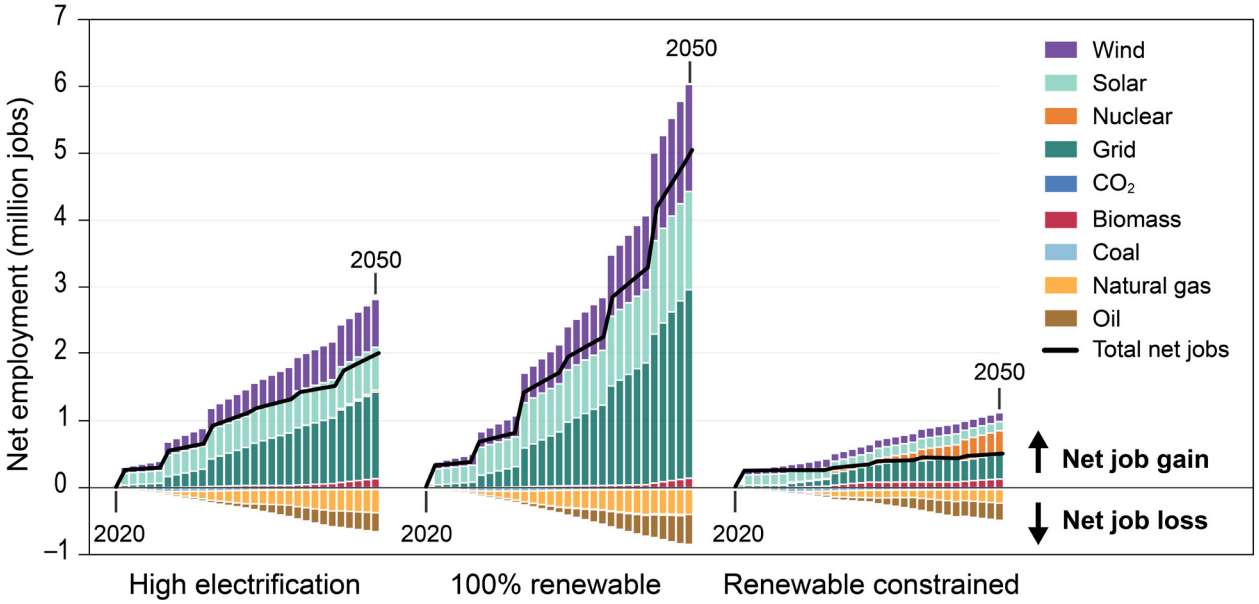
## Job opportunities are shifting due to climate change and climate action

Many US households are already feeling the economic impacts of climate change. Climate change is projected to impose a variety of new or higher costs on most households as healthcare, food, insurance, building, and repair costs become more expensive. Compounding climate stressors can increase segregation, income inequality, and reliance on social safety net programs. Quality of life is also threatened by climate change

in ways that can be more difficult to quantify, such as increased crime and domestic violence, harm to mental health, reduced happiness, and fewer opportunities for outdoor recreation and play. {11.3, 19.1, 19.3}

Climate change, and how the country responds, is expected to alter demand for workers and shift where jobs are available. For example, energy-related livelihoods in the Northern and Southern Great Plains are expected to shift as the energy sector transforms toward more renewables, low-carbon technologies, and electrification of more sectors of the economy. Losses in fossil fuel–related jobs are projected to be completely offset by greater increases in mitigation-related jobs, as increased demand for renewable energy and low-carbon technologies is expected to lead to long-term expansion in most states' energy and decarbonization workforce (Figure 1.12). Grid expansion and energy efficiency efforts are already creating new jobs in places like Nevada, Vermont, and Alaska, and advancements in biofuels and agrivoltaics (combined renewable energy and agriculture) provide economic opportunities in rural communities. {10.2, 11.3, 19.3, 25.3, 26.2, 29.3, 32.4}

Additional opportunities include jobs in ecosystem restoration and construction of energy-efficient and climate-resilient housing and infrastructure. Workforce training and equitable access to clean energy jobs, which have tended to exclude women and people of color, are essential elements of a just transition to a decarbonized economy. {5.3, 19.3, 20.3, 22.3, 25.3, 26.2, 27.3, 32.4}




### Energy Employment (2020–2050) for Alternative Net-Zero Pathways

**Employment gains in electrification and renewable energy industries are projected to far outpace job losses in fossil fuel industries.**

**Figure 1.12.** Despite decreases in the number of fossil fuel–related jobs, the overall number of energy jobs (specifically those involved in the supply of energy) relative to 2019 is generally projected to increase in net-zero-emissions energy scenarios between 2020 and 2050, although by much more in some scenarios than in others. {Figure 32.17} Adapted with permission from Jenkins et al. 2021.

(**top**; Golden, Colorado) Solar panels are pictured on the campus of the National Renewable Energy Laboratory. (**bottom left**; San Antonio, Texas) Participants in the 2022 Collegiate Wind Competition focus on offshore wind projects. (**bottom right**; Lexington, Virginia) Workers install fiber-optic cables. Rural broadband deployment is associated with higher incomes and lower unemployment rates. Photo credits: (top and bottom left) Werner Slocum/NREL [CC-BY-NC-ND 2.0]; (bottom right) Preston Keres, USDA

## Climate change is disrupting cultures, heritages, and traditions

As climate change transforms US landscapes and ecosystems, many deeply rooted community ties, pastimes, Traditional Knowledges, and cultural or spiritual connections to place are at risk. Cultural heritage—including buildings, monuments, livelihoods, and practices—is threatened by impacts on natural ecosystems and the built environment. Damages to archaeological, cultural, and historical sites further reduce opportunities to transfer important knowledge and identity to future generations. {6.1, 7.2, 8.3, 9.2, 10.1, 12.2, 16.1, 22.1, 23.1, 26.1, 27.6, 28.2; Introductions in Chs. 10, 30}

Many outdoor activities and traditions are already being affected by climate change, with overall impacts projected to further hinder recreation, cultural practices, and the ability of communities to maintain local heritage and a sense of place. {19.1}

For example:

- The prevalence of invasive species and harmful algal blooms is increasing as waters warm, threatening activities like swimming along Southeast beaches, boating and fishing for walleye in the Great Lakes, and viewing whooping cranes along the Gulf Coast. In the Northwest, water-based recreation demand is expected to increase in spring and summer months, but reduced water quality and harmful algal blooms are expected to restrict these opportunities. {24.2, 24.5, 26.3, 27.6}

- Ranges of culturally important species are shifting as temperatures warm, making them harder to find in areas where Indigenous Peoples have access (see Box 1.3). {11.2, 24.2, 26.1}
- Hikers, campers, athletes, and spectators face increasing threats from more severe heatwaves, wildfires, and floods and greater exposure to infectious disease. {15.1, 22.2, 26.3, 27.6}

Nature-based solutions and ecosystem restoration can preserve cultural heritage while also providing valuable local benefits, such as flood protection and new recreational opportunities. Cultural heritage can also play a key role in climate solutions, as incorporating local values, Indigenous Knowledge, and equity into design and planning can help reaffirm a community's connection to place, strengthen social networks, and build new traditions. {7.3, 26.1, 26.3, 30.5}

(**top left**; Glacier National Park, Montana) Wildfire smoke jeopardizes participation in outdoor sports and recreation. (**top right**; Boston Harbor, Massachusetts) Sea level rise threatens historical and archaeological sites on the Boston Harbor Islands. (**bottom**; Goose Island, Texas) Whooping cranes, which draw birdwatchers to the Gulf of Mexico, are at risk due to flooding, drought, and upstream water use. Photo credit: (top left) Andrew Parlette [CC BY 2.0]; (top right) cmh2315fl [CC BY-NC 2.0]; (bottom) Alan Schmierer [CC0 1.0].

# The Choices That Will Determine the Future

With each additional increment of warming, the consequences of climate change increase. The faster and further the world cuts greenhouse gas emissions, the more future warming will be avoided, increasing the chances of limiting or avoiding harmful impacts to current and future generations.

## Societal choices drive greenhouse gas emissions

The choices people make on a day-to-day basis—how to power homes and businesses, get around, and produce and use food and other goods—collectively determine the amount of greenhouse gases emitted. Human use of fossil fuels for transportation and energy generation, along with activities like manufacturing and agriculture, has increased atmospheric levels of carbon dioxide ($CO_2$) and other heat-trapping greenhouse gases. Since 1850, $CO_2$ concentrations have increased by almost 50%, methane by more than 156%, and nitrous oxide by 23%, resulting in long-term global warming. {2.1, 3.1; Ch. 2, Introduction}

The $CO_2$ not removed from the atmosphere by natural sinks lingers for thousands of years. This means that $CO_2$ emitted long ago continues to contribute to climate change today. Because of historical trends, cumulative $CO_2$ emissions from fossil fuels and industry in the US are higher than from any other country. To understand the total contributions of past actions to observed climate change, additional warming from $CO_2$ emissions from land use, land-use change, and forestry, as well as emissions of nitrous oxide and the shorter-lived greenhouse gas methane, should also be taken into account. Accounting for all of these factors and emissions from 1850–2021, emissions from the US are estimated to comprise approximately 17% of current global warming. {2.1}

Tami Phelps

Carbon dioxide, along with other greenhouse gases like methane and nitrous oxide, is well-mixed in the atmosphere. This means these gases warm the planet regardless of where they were emitted. For the first half of the 20th century, the vast majority of greenhouse gas emissions came from the US and Europe. But as US and European emissions have been falling (US emissions in 2021 were 17% lower than 2005 levels), emissions from the rest of the world, particularly Asia, have been rising rapidly. The choices the US and other countries make now will determine the trajectory of climate change and associated impacts for many generations to come (Figure 1.13). {2.1, 2.3; Ch. 32}

George Lorio

## Box 1.4. Global Warming Levels

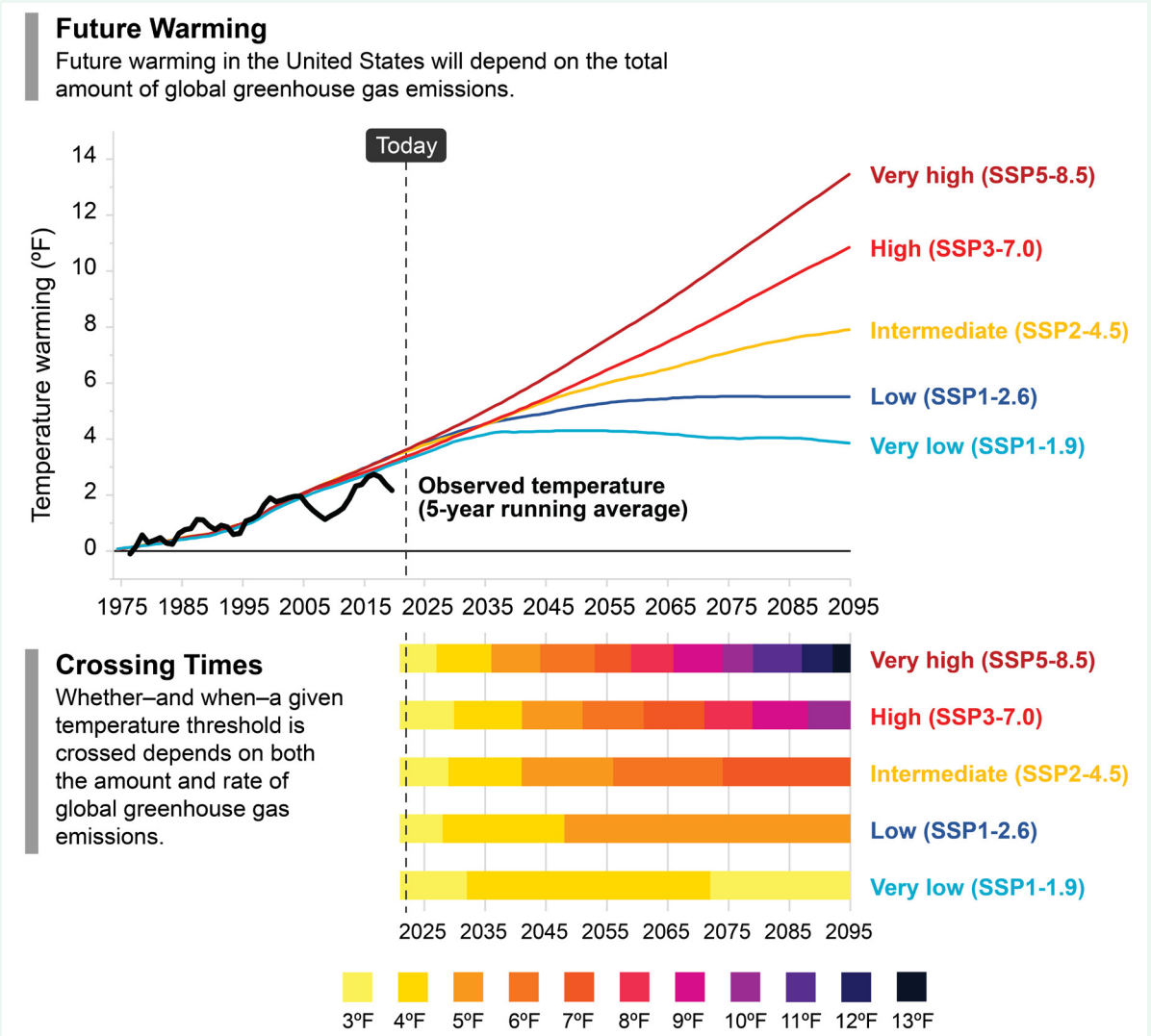
Because long-term societal actions are uncertain, climate modeling experts use different scenarios of plausible futures to represent a range of possible trajectories. These scenarios capture variables such as the relationship between human behavior, greenhouse gas emissions, Earth's responses to changes in the concentration of greenhouse gases in our atmosphere and ocean, and the resulting impacts, including temperature change and sea level rise. {3.3; Guide to the Report; App. 3}

Since there are uncertainties inherent in all of these factors—especially human behavior and the choices that determine emissions levels—the resulting range of projections are not predictions but instead reflect multiple potential future pathways. Future climate change under a given scenario is often expressed in one of two ways: as a range of potential outcomes in a future year (Figure 1.13a) or the time at which a specific outcome is expected (Figure 1.13b). {2.3, 3.3; App. 3}

Over the next decade, projected global warming is very similar across all scenarios. Updating energy infrastructure or making systemic economic and political changes takes time, thus temperature trajectories under different scenarios take time to diverge. {2.3}

By midcentury (2040–2070), differences between projected temperatures under higher and lower scenarios become apparent. By the end of the century, the global warming level—that is, how much the global average surface temperature increases above preindustrial levels—is expected to exceed 5.4°F (3°C) under high and very high scenarios (SSP3-7.0 and SSP5-8.5, respectively), and the world could see more than 7.2°F (4°C) of warming under a very high scenario (SSP5-8.5). Long-term global warming is expected to stay below 3.6°F (2°C) under a low scenario (SSP1-2.6) and can be limited to 2.7°F (1.5°C) only under a very low scenario (SSP1-1.9). {2.3}

The risk of exceeding a particular global warming level depends on future emissions. This means that projections are conditional: when or if the world reaches a particular level of warming is largely dependent on human choices. {2.3}




## Potential Warming Pathways in the United States

**When or if the US reaches a particular level of warming depends on global greenhouse gas emissions from human activities.**

**Figure 1.13.** How much warming the US will experience—and when a given temperature threshold is crossed—depends on future global emissions. The **top graph** shows observed change in US surface temperature during 1975–2022 (black line, 5-year averaged) and modeled historical (1975–2014) and projected (2015–2095) change in surface temperature compared to 1951–1980, annually averaged over all 50 states and Puerto Rico under different climate scenarios (multicolored lines; see Table 3 in the Guide to the Report). The **bottom graph** shows the same projections in a different way, highlighting the year in which the US crosses temperature thresholds under each scenario. The vertical dashed line represents the year 2023. Data for the US-Affiliated Pacific Islands and the US Virgin Islands are not available. See Figure 1.5 for observed US and global temperature changes since 1895. Adapted with permission from Figure TS.1 in Arias et al. 2021.

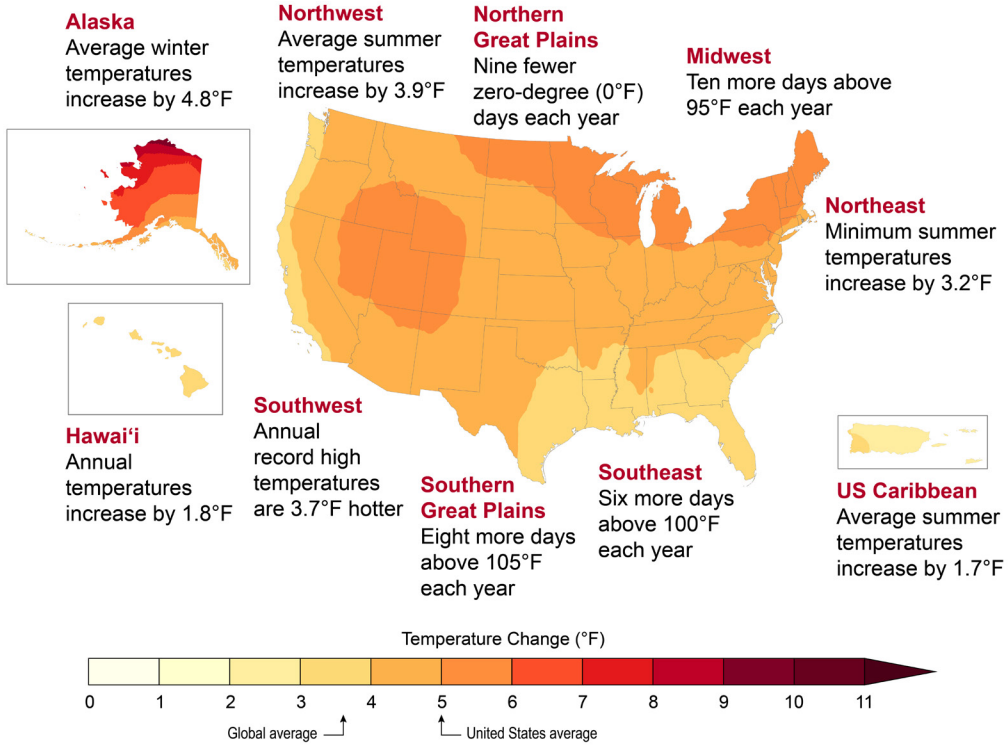
## Rising global emissions are driving global warming, with faster warming in the US

The observed global warming of about 2°F (1.1°C) over the industrial era is unequivocally caused by greenhouse gas emissions from human activities, with only very small effects from natural sources. About three-quarters of total emissions and warming (1.7°F [0.95°C]) have occurred since 1970. Warming would have been even greater without the land and ocean carbon sinks, which have absorbed more than half of the $CO_2$ emitted by humans. {2.1, 3.1, 7.2; Ch. 2, Introduction; Figures 3.1, 3.8}

The US is warming faster than the global average, reflecting a broader global pattern: land areas are warming faster than the ocean, and higher latitudes are warming faster than lower latitudes. Additional global warming is expected to lead to even greater warming in some US regions, particularly Alaska (Figure 1.14). {2.1, 3.4; Ch. 2, Introduction; App. 4}

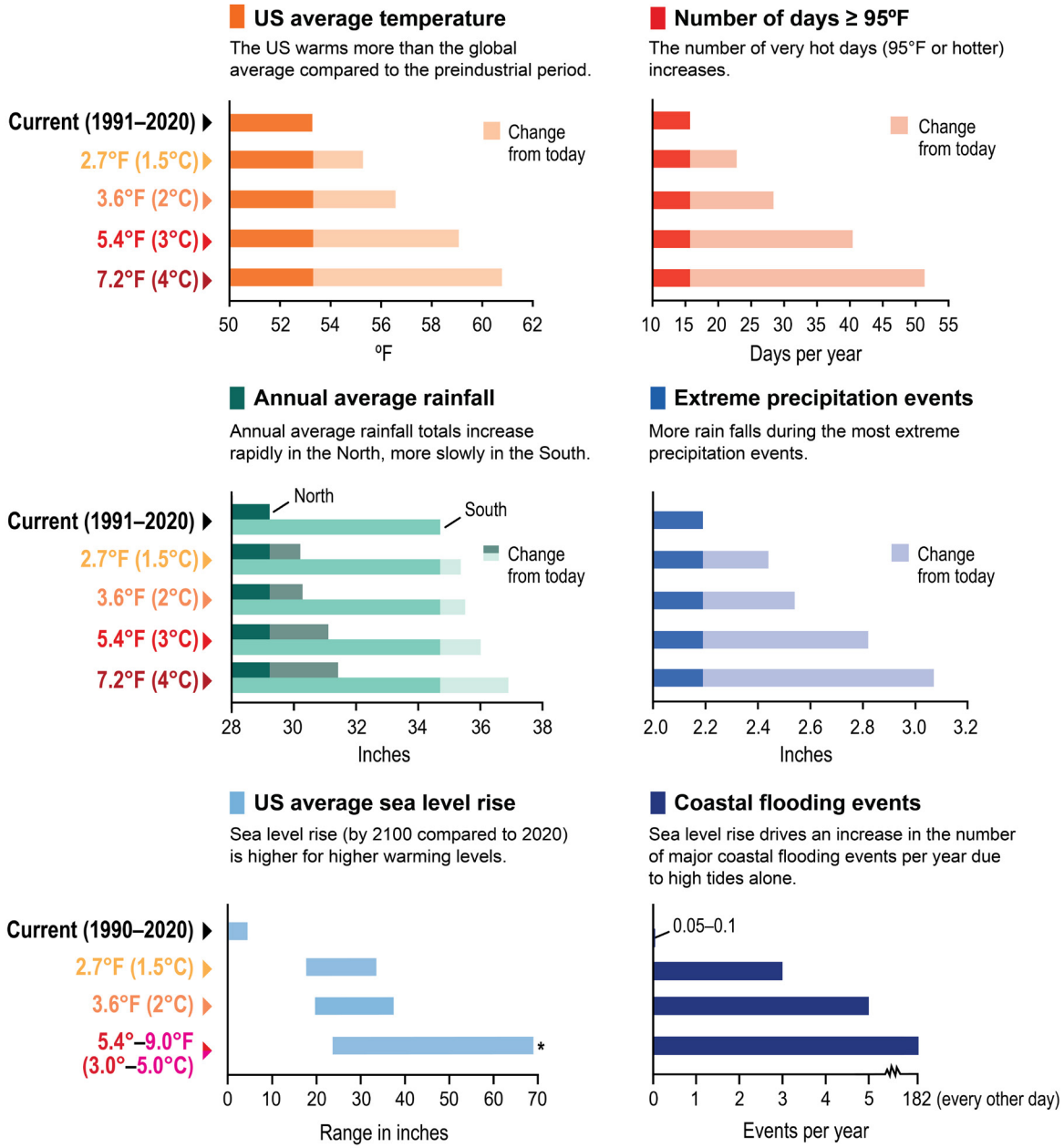
## Warming increases risks to the US

Rising temperatures lead to many large-scale changes in Earth's climate system, and the consequences increase with warming (Figure 1.15). Some of these changes can be further amplified through feedback processes at higher levels of warming, increasing the risk of potentially catastrophic outcomes. For example, uncertainty in the stability of ice sheets at high warming levels means that increases in sea level along the continental US of 3–7 feet by 2100 and 5–12 feet by 2150 are distinct possibilities that cannot be ruled out. The chance of reaching the upper end of these ranges increases as more warming occurs. In addition to warming more, the Earth warms faster in high and very high scenarios (SSP3-7.0 and SSP5-8.5, respectively), making adaptation more challenging. {2.3, 3.1, 3.4, 9.1}




**What would 3.6°F (2°C) of global warming feel like in the United States?**

**Figure 1.14.** As the world warms, the United States warms more on average. The map shows projected changes in annual surface temperature compared to the present day (1991–2020) under a global warming level of 3.6°F (2°C) above preindustrial levels (see Figure 2.9). Regional examples show how different temperature impacts would be experienced across the country at this level of warming. Figure credit: USGCRP, NOAA NCEI, and CISESS NC.




*Rise at the upper end of this range cannot be ruled out due to the possibility of rapid ice sheet loss. The amount of warming required to trigger such loss is not currently known but is assessed to be above 3.6°F (2°C).

## Consequences Are Greater at Higher Global Warming Levels

**At higher global warming levels, the US will experience more severe climate impacts.**

**Figure 1.15.** With each additional increment of global warming, climate impacts in the US are projected to be more severe: US average temperature warms more than the global average (**top left**), and the number of days per year at or above 95°F in the US increases (**top right**). Annual average US rainfall increases rapidly in the North and more slowly in the South (**center left**), and more rain falls during the most extreme precipitation events (**center right**). Sea level rise (range of projected increases by 2100 compared to 2020) is higher (**bottom left**), driving an increase in the number of major coastal flooding events per year due to high tides alone (**bottom right**). Temperature (averages and extremely hot days; top row) and extreme rainfall projections (center right) are averages for all 50 states and Puerto Rico. Average rainfall projections (center left) are shown for both the northern and southern US (above and below 37° latitude, respectively). Sea level rise (bottom left) and coastal flooding (bottom right) projections are averages for the contiguous United States. For sea level change estimates outside of the contiguous US, see Chapter 23 (for Puerto Rico and the US Virgin Islands), Chapter 30 (for Hawai'i and the US-Affiliated Pacific Islands), and Sweet et al. 2022 (for Alaska). Global warming levels refer to warming since preindustrial temperature conditions, defined as the 1851–1900 average. Figure credit: USGCRP, NOAA NOS, NASA, NOAA NCEI, and CISESS NC.

# How Climate Action Can Create a More Resilient and Just Nation

Large near-term cuts in greenhouse gas emissions are achievable through many currently available and cost-effective mitigation options. However, reaching net-zero emissions by midcentury cannot be achieved without exploring additional mitigation options. Even if the world decarbonizes rapidly, the Nation will continue to face climate impacts and risks. Adequately and equitably addressing these risks involves longer-term inclusive planning, investments in transformative adaptation, and mitigation approaches that consider equity and justice.

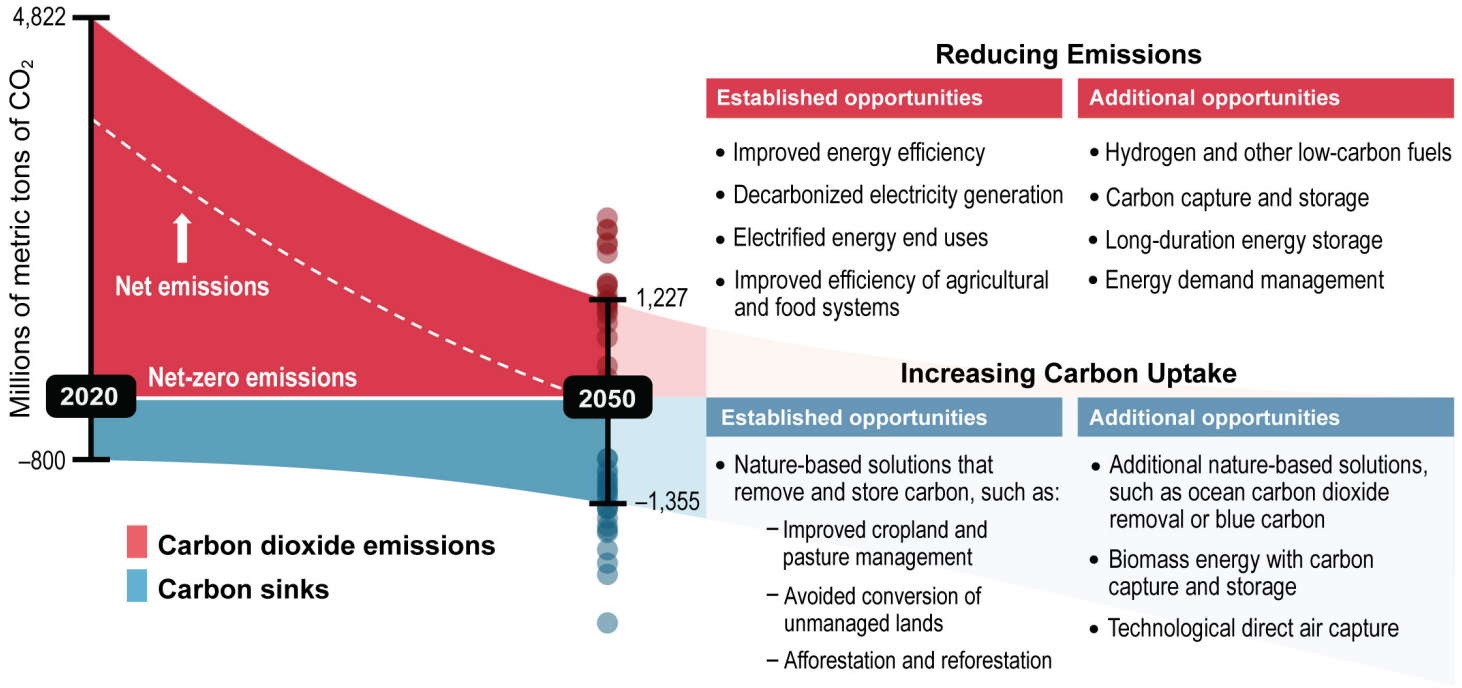
## Available mitigation strategies can deliver substantial emissions reductions, but additional options are needed to reach net zero

Limiting global temperature change to well below 2°C (3.6°F) requires reaching net-zero $CO_2$ emissions globally by 2050 and net-zero emissions of all greenhouse gases from human activities within the following few decades (see "Meeting US mitigation targets means reaching net-zero emissions" above). Net-zero emissions pathways involve widespread implementation of currently available and cost-effective options for reducing emissions alongside rapid expansion of technologies and methods to remove carbon from the atmosphere to balance remaining emissions. However, to reach net-zero emissions, additional mitigation options need to be explored (Figure 1.16). Pathways to net zero involve large-scale technological, infrastructure, land-use, and behavioral changes and shifts in governance structures. {5.3, 6.3, 9.2, 9.3, 10.4, 13.2, 16.2, 18.4, 20.1, 24.1, 25.5, 30.5, 32.2, 32.3; Focus on Blue Carbon}

Scenarios that reach net-zero emissions include some of the following key options:

- Decarbonizing the electricity sector, primarily through expansion of wind and solar energy, supported by energy storage {32.2}
- Transitioning to transportation and heating systems that use zero-carbon electricity or low-carbon fuels, such as hydrogen {5.3, 13.1, 32.2, 32.3}
- Improving energy efficiency in buildings, appliances, and light- and heavy-duty vehicles and other transportation modes {5.3, 13.3, 32.2}
- Implementing urban planning and building design that reduces energy demands through more public transportation and active transportation and lower cooling demands for buildings {12.3, 13.1, 32.2}
- Increasing the efficiency and sustainability of food production, distribution, and consumption {11.1, 32.2}
- Improving land management to decrease greenhouse gas emissions and increase carbon removal and storage, with options ranging from afforestation, reforestation, and restoring coastal ecosystems to industrial processes that directly capture and store carbon from the air {5.3, 6.3, 8.3, 32.2, 32.3; Focus on Blue Carbon}

## Portfolio of Mitigation Options for Achieving Net Zero by 2050




**Reaching net zero by 2050 in the US will involve a mix of reductions in greenhouse gas emissions and increases in carbon dioxide removal.**

**Figure 1.16.** Reaching net-zero emissions (horizontal white line) by midcentury in the US would mean deep reductions in emissions of carbon dioxide ($CO_2$) and other greenhouse gases (**top side of figure**; red), with residual emissions balanced by additional removal of $CO_2$ from the atmosphere (**bottom side of figure**; blue). The dashed white line shows net emissions to the atmosphere (the sum of carbon sources and carbon sinks). The dots at 2050 show ranges of emissions and uptake for energy model scenarios explored in detail in Chapter 32. Model scenarios that achieve these targets project a mix of established opportunities for reducing emissions and increasing carbon sinks. Among these, energy efficiency, decarbonized electricity (mainly renewables), and end-use electrification are critical for the energy sector. While not exhaustive, the list also includes additional opportunities, many of which are emerging technologies that will be integral to reaching net zero. These include options like use of hydrogen and low-carbon fuels to further reduce emissions in difficult-to-decarbonize sectors and greatly increasing $CO_2$ removal. Figure credit: EPA; University of California, Irvine; NOAA NCEI; and CISESS NC.

Due to large declines in technology and deployment costs over the last decade (Figure 1.2), decarbonizing the electricity sector is expected to be largely driven by rapid growth in renewable energy. Recent legislation is also expected to increase deployment rates of low- and zero-carbon technology. To reach net-zero targets, the US will need to add new electricity-generating capacity, mostly wind and solar, faster than ever before. This infrastructure expansion may drastically increase demand for products (batteries, solar photovoltaics) and resources, such as metals and critical minerals. Near-term shortages in minerals and metals due to increased demand can be addressed by increased recycling, for example, which can also reduce dependence on imported materials. {5.2, 5.3, 17.2, 25.3, 32.2, 32.4; Focus on Risks to Supply Chains}

Most US net-zero scenarios require $CO_2$ removal from the atmosphere to balance residual emissions, particularly from sectors where decarbonization is difficult. In these scenarios, nuclear and hydropower capacity are maintained but not greatly expanded; natural gas–fired generation declines, but more slowly if coupled with carbon capture and storage. {32.2}

Nature-based solutions that restore degraded ecosystems and preserve or enhance carbon storage in natural systems like forests, oceans, and wetlands, as well as agricultural lands, are cost-effective mitigation strategies. For example, with conservation and restoration, marine and coastal ecosystems could capture and store enough atmospheric carbon each year to offset about 3% of global emissions (based on 2019 and 2020 emissions). Many nature-based solutions can provide additional benefits, like improved ecosystem resilience, food production, improved water quality, and recreational opportunities. {8.3; Boxes 7.2, 32.2; Focus on Blue Carbon}

## Adequately addressing climate risks involves transformative adaptation

While adaptation planning and implementation has advanced in the US, most adaptation actions to date have been incremental and small in scale (see Table 1.3). In many cases, more transformative adaptation will be necessary to adequately address the risks of current and future climate change. {31.1, 31.3}.

**Table 1.3. Incremental Versus Transformative Adaptation Approaches**

| | Examples of incremental adaptation | Examples of transformative adaptation |
|---|---|---|
| | Using air-conditioning during heatwaves | Redesigning cities and buildings to address heat |
| | Reducing water consumption during droughts | Shifting water-intensive industry to match projected rainfall patterns |
| | Elevating homes above flood waters | Directing new housing development to less flood-prone areas |

Transformative adaptation involves fundamental shifts in systems, values, and practices, including assessing potential trade-offs, intentionally integrating equity into adaptation processes, and making systemic changes to institutions and norms. While barriers to adaptation remain, many of these can be overcome with financial, cultural, technological, legislative, or institutional changes. {31.1, 31.2, 31.3}.

Adaptation planning can more effectively reduce climate risk when it identifies not only disparities in how people are affected by climate change but also the underlying causes of climate vulnerability. Transformative adaptation would involve consideration of both the physical and social drivers of vulnerability and how they interact to shape local experiences of vulnerability and disparities in risk. Examples include understanding how differing levels of access to disaster assistance constrain recovery outcomes or how disaster damage exacerbates long-term wealth inequality. Effective adaptation, both incremental and transformative, involves developing and investing in new monitoring and evaluation methods to understand the different values of, and impacts on, diverse individuals and communities. {9.3, 19.3, 31.2, 31.3, 31.5}

Transformative adaptation would require new and better-coordinated governance mechanisms and cooperation across all levels of government, the private sector, and society. A coordinated, systems-based approach can support consideration of risks that cut across multiple sectors and scales, as well as the development of context-specific adaptations. For example, California, Florida, and other states have used informal regional collaborations to develop adaptation strategies tailored to their area. Adaptation measures that are designed and implemented using inclusive, participatory planning approaches and leverage coordinated governance and financing have the greatest potential for long-term benefits, such as improved quality of life and increased economic productivity. {10.3, 18.4, 20.2, 31.4}

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## Mitigation and adaptation actions can result in systemic, cascading benefits

Actions taken now to accelerate net emissions reductions and adapt to ongoing changes can reduce risks to current and future generations. Mitigation and adaptation actions, from international to individual scales, can also result in a range of benefits beyond limiting harmful climate impacts, including some immediate benefits (Figure 1.1). The benefits of mitigation and proactive adaptation investments are expected to outweigh the costs. {2.3, 13.3, 14.5, 15.3, 17.4, 22.1, 31.6, 32.4; Introductions in Chs. 17, 31}

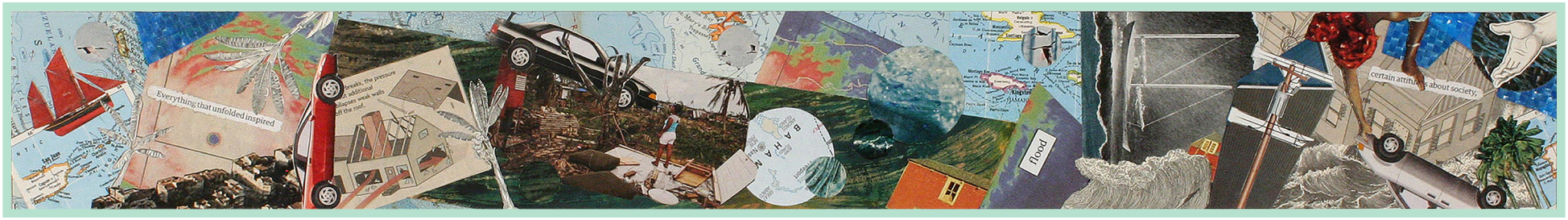
- Accelerating the deployment of low-carbon technologies, expanding renewable energy, and improving building efficiency can have significant near-term social and economic benefits like reducing energy costs and creating jobs. {32.4}
- Transitioning to a carbon-free, sustainable, and resilient transportation system can lead to improvements in air quality, fewer traffic fatalities, lower costs to travelers, improved mental and physical health, and healthier ecosystems. {13.3}
- Reducing emissions of short-lived climate pollutants like methane, black carbon, and ozone provides immediate air quality benefits that save lives and decrease the burden on healthcare systems while also slowing near-term warming. {11.1, 14.5, 15.3}
- Green infrastructure and nature-based solutions that accelerate pathways to net-zero emissions through restoration and protection of ecological resources can improve water quality, strengthen biodiversity, provide protection from climate hazards like heat extremes or flooding, preserve cultural heritage and traditions, and support more equitable access to environmental amenities. {8.3, 15.3, 20.3, 24.4, 30.4; Focus on Blue Carbon}
- Strategic planning and investment in resilience can reduce the economic impacts of climate change, including costs to households and businesses, risks to markets and supply chains, and potential negative impacts on employment and income, while also providing opportunities for economic gain. {9.2, 19.3, 26.2, 31.6; Focus on Risks to Supply Chains}
- Improving cropland management and climate-smart agricultural practices can strengthen the resilience and profitability of farms while also increasing soil carbon uptake and storage, reducing emissions of nitrous oxide and methane, and enhancing agricultural efficiency and yields. {11.1, 24.1, 32.2}

Climate actions that incorporate inclusive and sustained engagement with overburdened and underserved communities in the design, planning, and implementation of evidence-based strategies can also reduce existing disparities and address social injustices. {24.3, 31.2, 32.4}

## Transformative climate actions can strengthen resilience and advance equity

Fossil fuel–based energy systems have resulted in disproportionate public health burdens on communities of color and/or low-income communities. These same communities are also disproportionately harmed by climate change impacts. {13.4, 15.2, 32.4}

A "just transition" is the process of responding to climate change with transformative actions that address the root causes of climate vulnerability while ensuring equitable access to jobs; affordable, low-carbon energy; environmental benefits such as reduced air pollution; and quality of life for all. This involves reducing impacts to overburdened communities, increasing resources to underserved communities, and integrating diverse worldviews, cultures, experiences, and capacities into mitigation and adaptation actions. As the country shifts to low-carbon energy industries, a just transition would include job creation




Melanie Mills

and training for displaced fossil fuel workers and addressing existing racial and gender disparities in energy workforces. For example, Colorado agencies are creating plans to guide the state's transition away from coal, with a focus on economic diversification, job creation, and workforce training for former coal workers. The state's plan also acknowledges a commitment to communities disproportionately impacted by coal power pollution. {5.3, 13.4, 14.3, 15.2, 16.2, 20.3, 31.2, 32.4; Figure 20.1}

A just transition would take into account key aspects of environmental justice:

- Recognizing that certain people have borne disparate burdens related to current and historical social injustices and, thus, may have different needs
- Ensuring that people interested in and affected by outcomes of decision-making processes are included in those procedures through fair and meaningful engagement
- Distributing resources and opportunities over time, including access to data and information, so that no single group or set of individuals receives disproportionate benefits or burdens

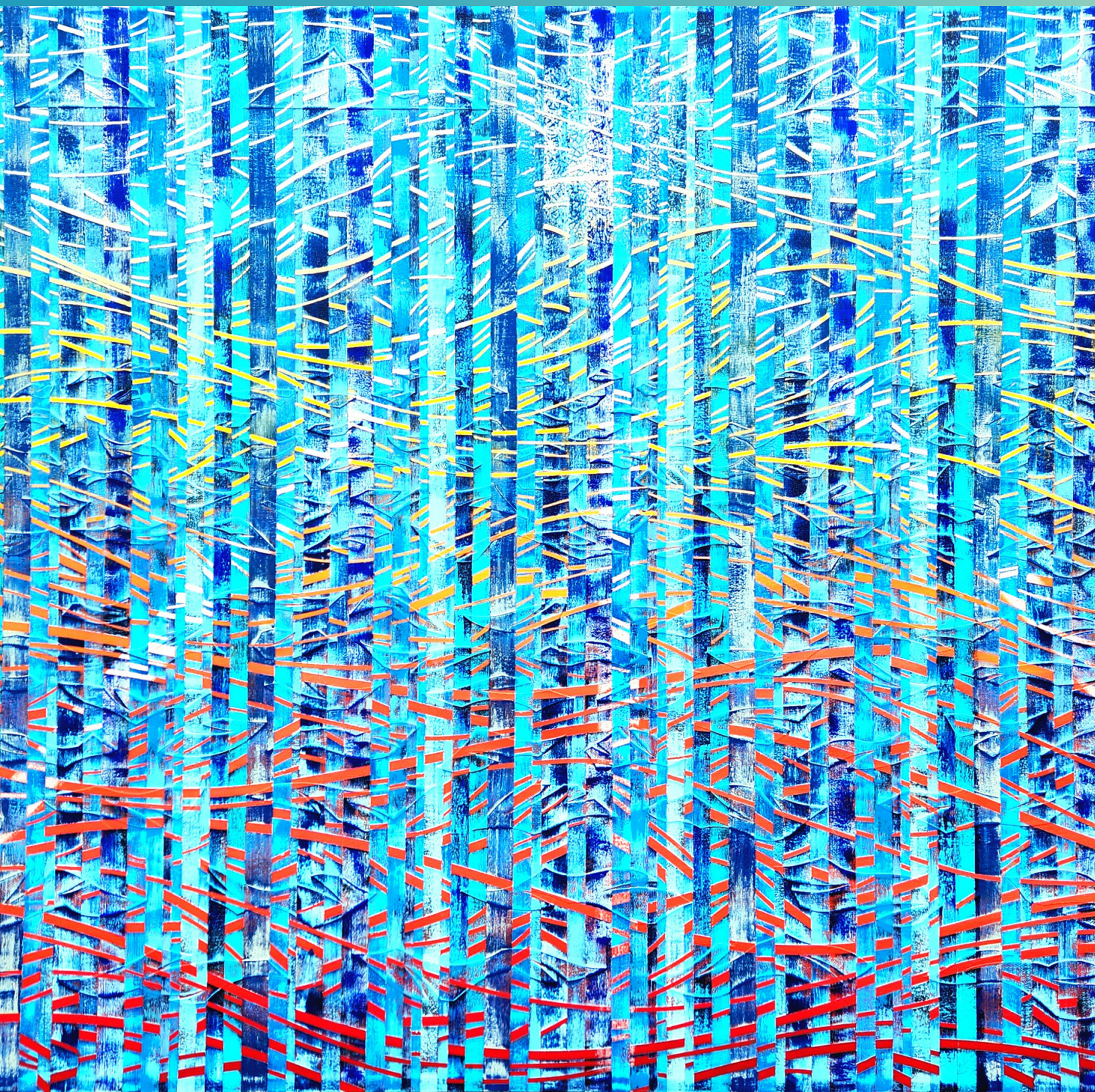
{20.3; Figure 20.1}

An equitable and sustainable US response to climate change has the potential to reduce climate impacts while improving well-being, strengthening resilience, benefiting the economy, and, in part, redressing legacies of racism and injustice. Transformative adaptation and the transition to a net-zero energy system come with challenges and trade-offs that would need to be considered to avoid exacerbating or creating new social injustices. For example, transforming car-centric transportation systems to emphasize public transit and walkability could increase accessibility for underserved communities and people with limited mobility—if user input and equity are intentionally considered. {13.4, 20.3, 31.3, 32.4; Ch. 31, Introduction}

Equitable responses that assess trade-offs strengthen community resilience and self-determination, often fostering innovative solutions. Engaging communities in identifying challenges and bringing together diverse voices to participate in decision-making allows for more inclusive, effective, and transparent planning processes that account for the structural factors contributing to inequitable climate vulnerability. {9.3, 12.4, 13.4, 20.2, 31.4}

Fifth National Climate Assessment: Chapter 2

# Climate Trends



# Chapter 2. Climate Trends

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# Introduction

Human activities are changing the climate. The evidence for warming across multiple aspects of the Earth system is incontrovertible, and the science is unequivocal that increases in atmospheric greenhouse gases are driving many observed trends and changes (KM 3.1). There are more greenhouse gases in the atmosphere primarily because humans have burned and continue to burn fossil fuels for transportation and energy generation.[1] Industrial processes, deforestation, and agricultural practices also increase greenhouse gases in the atmosphere.[1] As a result of increases in the atmospheric concentrations of these heat-trapping gases, the planet is on average about 2°F (1.1°C) warmer than it was in the late 1800s.[2,3,4,5] No natural processes known to science could have caused this long-term temperature trend. The only credible explanation for the observed warming is human activities (Ch. 3).

Climate change is happening now in the United States. Including Alaska, the continental US has been warming about 60% faster than the planet as a whole since 1970. This temperature change has driven increases in the frequency and severity of some extreme events, consistent with the scientific understanding of climate change (Ch. 3). There has always been extreme weather, which occurs even in an unchanged climate due to the natural variability of the Earth system. However, recent advances in attribution science (KM 3.3) mean that the role of climate change in some extreme events can now be quantified in real time.[6,7] For example, climate change made the record-breaking Pacific Northwest heatwave of June 2021 2° to 4°F hotter,[8] and in 2017, Hurricane Harvey's rainfall was estimated to be about 15%–20% heavier than it would have been without human-caused warming.[9,10,11]

Climate change is already affecting people in the United States. Extreme heat was estimated to be responsible for more than 700 deaths per year between 2004 and 2018,[12] although some estimates put heat-related mortality closer to 1,300 deaths annually.[13,14] Disasters are now coming more frequently and causing more damage. In the 1980s, the country experienced, on average, one (inflation-adjusted) billion-dollar weather disaster every four months.[15] Now there is one, on average, every three weeks.[15]

Disaster risk in a complex society such as the United States is never determined simply by extreme weather events. It also depends strongly on exposure (who or what lies in the path of hazards) and vulnerability (their ability to cope with hazards). Climate change interacts with existing social, political, and economic structures—increases in property values as well as increased development in hazard hotspots[16] have also contributed to the increase in billion-dollar disasters—and exacerbates existing inequalities. Certain groups are more vulnerable to extreme events due to socioeconomic or demographic factors. Americans over 65 are several times more likely to die of heat-related cardiovascular disease than younger people, while Black Americans die from heat-related diseases at a rate twice that of the general population.[17] The extreme rainfall brought by Hurricane Harvey increased the flooded area in the Greater Houston area by 14%,[18] which led to 32% more homes flooded in Harris County,[19] with a disproportionate impact on low-income Hispanic neighborhoods. The spatial distribution of climate impacts partially reflects current and past policy choices: low-income neighborhoods, including those historically affected by redlining or other discriminatory policies, can be as much as 12°F hotter during heatwaves than wealthier neighborhoods in the same city[20] and are at a substantially higher risk of flooding.[21]

Climate change has other wide-ranging consequences for people's health and well-being (KM 15.1) and the land and ocean ecosystems on which we depend (Chs. 8, 10). The 2021 Pacific Northwest heatwave, which resulted in more than 1,400 heat-related fatalities, also led to widespread die-offs of shellfish and other marine organisms (Box 10.1), tree and crop damage, and other impacts on the region's ecosystems.[15,22] Western wildfires, made more severe by climate change (Focus on Western Wildfires), have destroyed towns and infrastructure and contributed to an increase in the frequency and persistence of high levels of

air pollution across the US West (Chs.14, 15).[23] These extreme events occur against a changing backdrop as climate change pushes aspects of the Earth system into a "new normal."

Long-term warming trends are associated with shifts in other aspects of the climate system. For example, both drought in the western US[24] and heavier precipitation and increased flood risk across much of the US[25] are linked to rising temperatures (KM 3.5). Sea level rise threatens the coasts (Ch. 9; Figure A4.10) and makes storm surges higher. Scientists cannot rule out the possibility of still more dramatic shifts if certain tipping elements trigger rapid and irreversible changes. While immediate and aggressive reductions in greenhouse gas emissions can mitigate future warming (KM 32.2) and reduce the risk of exceeding tipping points, temperatures will continue to increase until emissions of carbon dioxide reach net zero. When or if warming stops, long-term responses to the temperature changes that have already occurred will continue to drive changes for decades. Put simply, communities across the country are built for a climate that no longer exists.

## Key Message 2.1

## Climate Is Changing, and Scientists Understand Why

It is unequivocal that human activities have increased atmospheric levels of carbon dioxide and other greenhouse gases. It is also unequivocal that global average temperature has risen in response. Observed warming over the continental United States and Alaska is higher than the global average (*virtually certain, very high confidence*). Long-term changes have been observed in many other aspects of the climate system (*very high confidence*). The Earth system is complex and interconnected, which means changes in faraway regions are *virtually certain* to affect the United States (*very high confidence*).

Humans are increasing atmospheric concentrations of planet-warming gases, including the three main greenhouse gases produced by human activities: carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$; Table 2.1; Figure A4.3). Since 1850, carbon dioxide concentrations have increased by more than 47%, nitrous oxide by 23%, and methane by more than 156%.[1] Methane is a more potent greenhouse gas than $CO_2$ but is shorter-lived and present in lower concentrations than $CO_2$. Nitrous oxide is both long-lived and more potent, but its concentrations are also lower than $CO_2$. Strong reductions in emissions of both $CO_2$ and non-$CO_2$ greenhouse gases are required to limit human-induced global warming to specific levels.[26]

**Table 2.1. Concentrations of Greenhouse Gases That Cause Global Warming Are Increasing**

Human activities have increased atmospheric concentrations of the three main greenhouse gases: carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). Shown below are the concentrations in 1850 and 2020 for all three gases, along with information on the atmospheric lifetimes, sources, and sinks (processes by which the gas is removed from the atmosphere).

| Greenhouse Gas | 1850 Concentration | 2020 Concentration | Lifetime | Sources | Sinks |
|---|---|---|---|---|---|
| **Carbon dioxide ($CO_2$)** | 280 parts per million (ppm)[27] | 412 ppm[28] | See below* | Human activities: fossil fuel use, industrial processes, and changes in land use such as deforestation, land clearing for agriculture, and soil degradation. Natural sources: oceans, animal and plant respiration, decomposition, forest fires, volcanic eruptions. | Uptake by the biosphere on land and ocean and formation of calcium carbonate and carbonate ion leading to ocean acidification and land-based weathering |
| **Methane ($CH_4$)** | 700 parts per billion (ppb)[29] | 1,878 ppb[30] | 9.1 ± 0.09 years | Human activities: agriculture, waste management, energy use, and biomass burning. Natural sources: geological, oceanic hydrates, permafrost, termites, wild animals. | Chemical reactions in the atmosphere and soil uptake |
| **Nitrous oxide ($N_2O$)** | 270 ppb[1] | 333 ppb[31] | 116 ± 9 years[32] | Human activities: agriculture, fossil fuel combustion, biomass/ biofuel burning, and wastewater; atmospheric nitrogen deposition on ocean and land. Natural sources: rivers, estuaries and coastal zones, open oceans, soils under natural vegetation, atmospheric chemistry. | Stratospheric destruction via photolysis or broken down by chemical reactions |

* Carbon dioxide's lifetime cannot be represented with a single value since $CO_2$ moves among different reservoirs within the ocean–atmosphere–land system (see "Carbon Cycle," App. 5). The rate at which this transfer of $CO_2$ happens between reservoirs can vary from months to thousands of years, thus making it unrealistic to provide a single numerical value for the lifetime of $CO_2$, unlike $CH_4$ and $N_2O$, which have specific chemical loss mechanisms in the atmosphere. Also see https://www.epa.gov/climate-indicators/greenhouse-gases.

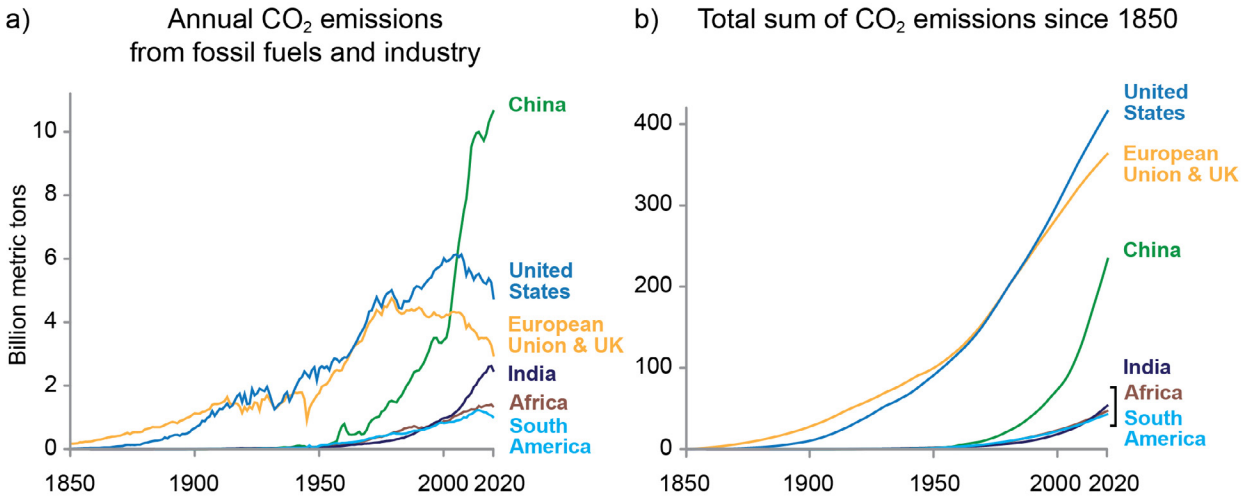
## $CO_2$ Emitted Long Ago Continues to Contribute to Climate Change Today

The carbon dioxide not removed from the atmosphere by natural sinks lingers for thousands of years. This means $CO_2$ emitted long ago continues to contribute to climate change today. The long lifetime of atmospheric $CO_2$ is one of the primary reasons why the COVID-19 pandemic–related reduction in greenhouse gas emissions—a decrease of 7% between 2019 and 2020[33,34,35]—had no measurable impact on atmospheric $CO_2$ concentrations and little effect on global temperatures (Focus on COVID-19 and Climate Change).[36,37] Because of historical trends, cumulative $CO_2$ emissions from fossil fuels and industry in the US are higher than from any other country (Figure 2.1b).

Carbon dioxide, along with other greenhouse gases like methane and nitrous oxide, is well-mixed in the atmosphere. This means these gases warm the planet regardless of where they were emitted, and all countries that emit them contribute to the warming of the entire globe. For the first half of the 20th century, the vast majority of greenhouse gas emissions came from the United States and Europe, but emissions from the rest of the world, particularly Asia, have been rising rapidly (Figure 2.1a). In 2021, for example, US emissions were 17% lower than 2005 levels and falling. Currently, the country that emits the most $CO_2$ on an annual basis is China.

In order to understand the total contributions of past actions to observed climate change, additional warming from $CO_2$ emissions from land use, land-use change, and forestry, as well as emissions of nitrous oxide and the shorter-lived greenhouse gas methane, should also be taken into account alongside cumulative fossil $CO_2$ emissions. Accounting for all these factors and emissions from 1850–2021, US emissions are estimated to comprise approximately 17% of current global warming, China 12%, European Union 10%, and emissions from the 47 least-developed countries collectively 6%.[38] The present is shaped by the past; future global warming depends on decisions made today (KM 2.3).

### Greenhouse Gas Emissions from the US and Other Sources




**China is now the largest single-country emitter of carbon dioxide on an annual basis. The United States and Europe have emitted the majority of cumulative carbon dioxide.**

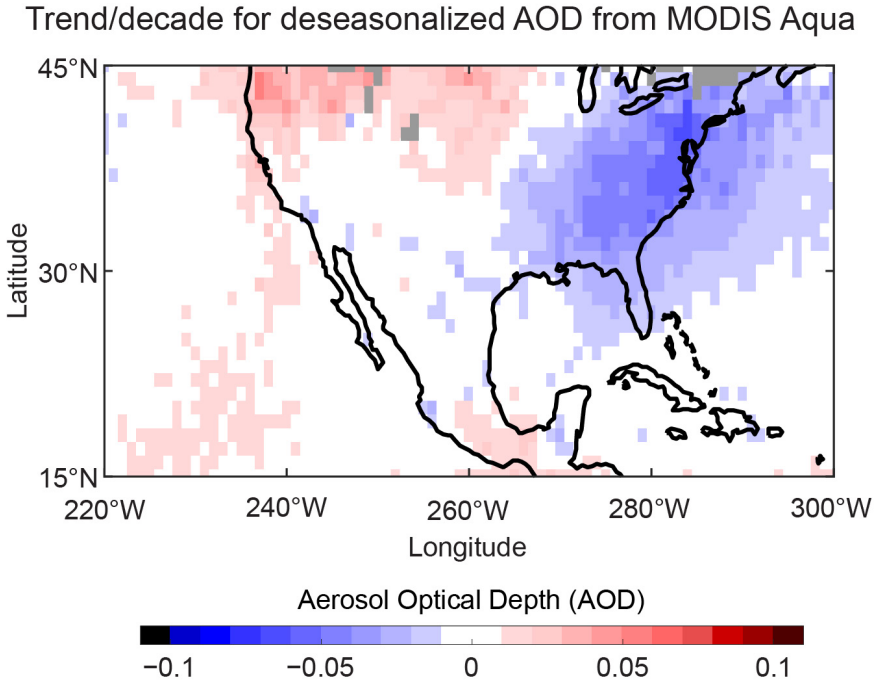
**Figure 2.1.** Panel (**a**) shows the annual total carbon dioxide ($CO_2$) emissions from fossil fuels and industry for selected world regions. China is currently the world's largest emitter of $CO_2$. Emissions from the US and the European Union and UK are large and falling; India, Africa, and South America emit less $CO_2$ on an annual basis. Panel (**b**) shows the cumulative $CO_2$ emissions of the same world regions. Some $CO_2$ emitted decades ago remains in the atmosphere today, causing the climate changes now being experienced. Figure credit: Project Drawdown.

## *Greenhouse Gases Are Not the Only Air Pollutants That Affect the Climate*

Many of the human activities that produce greenhouse gases also produce small airborne particles known as aerosols. Aerosol emissions are an important constituent of air pollution, which is responsible for more excess deaths in the United States than murders and car accidents combined.[39] Aerosols also have climate impacts: they can scatter or absorb sunlight, which have cooling and warming effects, respectively.

Aerosols also affect climate through their effects on clouds (Ch. 3). Increased global aerosol emissions have primarily cooled the planet, partially counteracting the warming caused by greenhouse gases, but compared to $CO_2$ aerosols are more localized and shorter lived. Aerosol emissions in the US have dramatically decreased since the passage of the Clean Air Act and subsequent pollution control legislation (Figure 2.2), global aerosol emissions have fallen, and the location of peak aerosol emissions has shifted from North America and Europe to South and East Asia. COVID-19–related shutdowns (see Focus on COVID-19 and Climate Change) led to decreases in aerosol emissions, reducing their cooling effect. This led to a small and temporary global warming estimated at 0.05°F.[40] Long-term reductions in aerosol emissions would further reduce the cooling effect of aerosols,[41,42] which means that even stronger reductions in greenhouse gases would be required to limit warming to specific levels.

## Observed Trends in Aerosol Optical Depth from 2002 to 2021



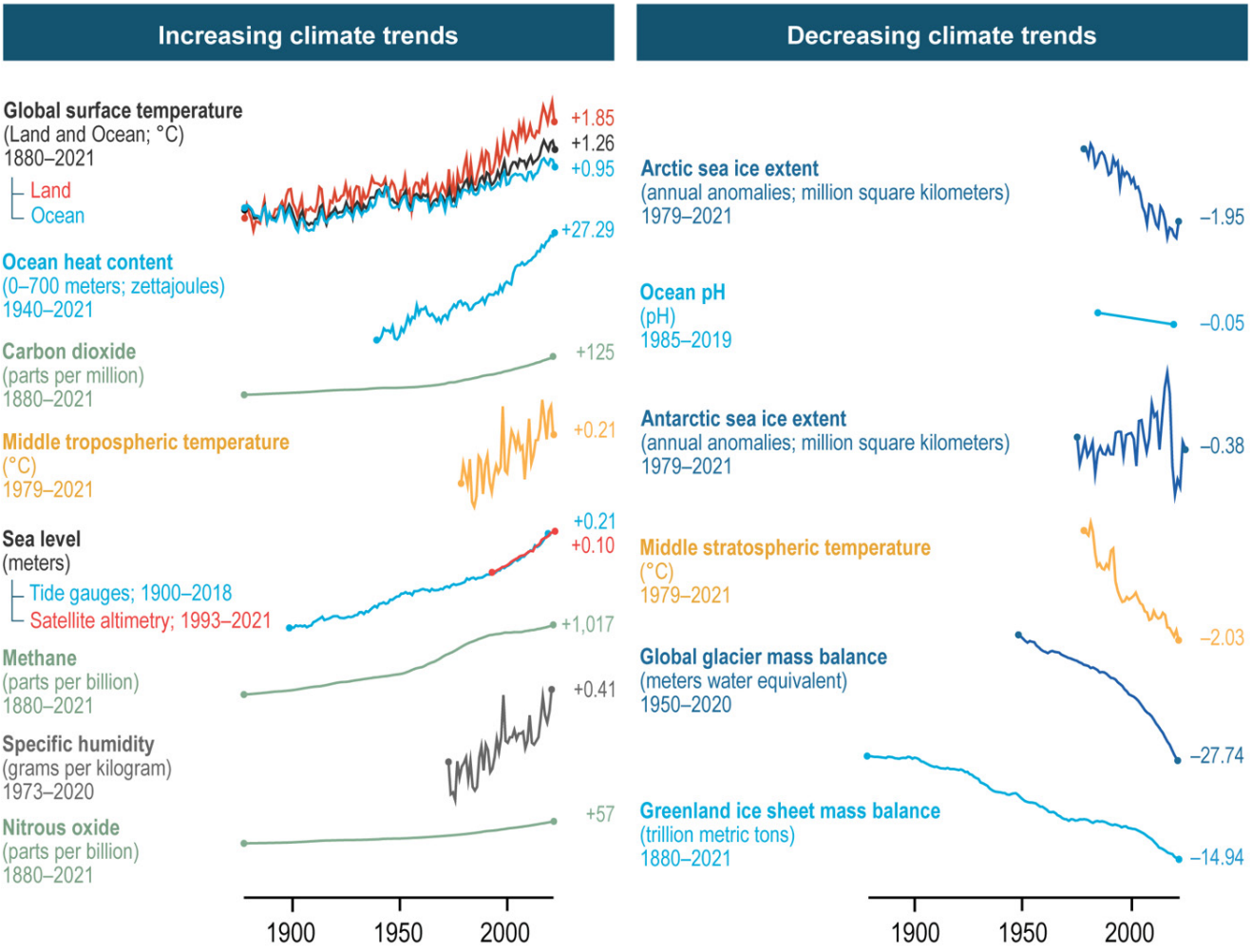

**Trends in aerosol optical depth show decreases in aerosol pollution across the eastern United States.**

**Figure 2.2.** Aerosol pollution over and downwind of the eastern US has decreased significantly in recent decades, resulting in both improved air quality and reduced cooling effects. Aerosols are tiny particles in the air that are associated with respiratory disease. Reduction of these particles means less impact on human health. These particles also reflect sunlight back to space, thus cooling the Earth's atmosphere. Reduction of these particles means less sunlight is reflected resulting in reduced cooling effects. This figure shows the trend from July 2002 to December 2021 in aerosol optical depth (AOD), a unitless measure of the total amount of aerosols in the atmosphere, as derived from satellite observations. The trend is calculated from deseasonalized AOD anomaly and is shown as change per decade. The trend over and downwind of the eastern US is significant at the 95% confidence level. Figure credit: NASA Langley Research Center.

## *Climate Change Is Already Here*

Global average temperatures over the past decade (2012–2021) were close to 2°F (1.1°C) warmer than the preindustrial period (1850–1899).[2,3,4,5] This warming has been accompanied by several large-scale changes: loss of glaciers, ice sheet mass, and sea ice; ocean warming, acidification, and deoxygenation; increases in ocean heat content and marine heatwaves; increases in atmospheric humidity; shifting rainfall patterns and more frequent heavy precipitation; seasonal shifts including shorter winters and earlier spring and summer seasons; and changes in the biosphere (such as land and ocean species shifting poleward). Global average sea levels over the past decade were also higher than in the preindustrial period by between 7 and 9.5 inches, with more than half of this rise occurring since 1980.[43,44,45] A subset of notable global climate trends is shown in Figure 2.3.

### Evidence for Climate Change Across Multiple Variables




**Changes across the Earth system reflect the influence of human activities on the climate.**

**Figure 2.3.** Climate change is apparent in many different aspects of the Earth system between 1880 and 2021. Many of these changes are evidence for a human fingerprint on the climate, reflecting the current scientific understanding of how the planet responds to external influences (Ch. 3). Global changes between the start and end of each time series are shown as numerical values to the right of each chart and are calculated by fitting each time series with a localized linear regression with a bandwidth of 30 years. Figure credit: Stripe Inc., NOAA NCEI, and CISESS NC.

## The Changes We Face Are Unprecedented in Human History

Bubbles of ancient air trapped in ice cores can be used to reconstruct atmospheric concentrations of greenhouse gases over the last 800,000 years. These concentrations rise and fall due to natural processes, but human activities have increased greenhouse gases in the atmosphere rapidly and to levels unprecedented in the history of human life on Earth. Other paleoclimatic evidence indicates that the last time atmospheric $CO_2$ concentrations were as high as today was approximately 3.2 million years ago,[46,47] a time when global average sea levels were 18–63 feet higher than today.[48] Evidence from multiple proxy-based reconstructions of the past indicates that the rate of increase of global surface temperatures observed over the past several decades is unprecedented over the past 2,000 years.[49]

## The Climate in the United States Is Changing

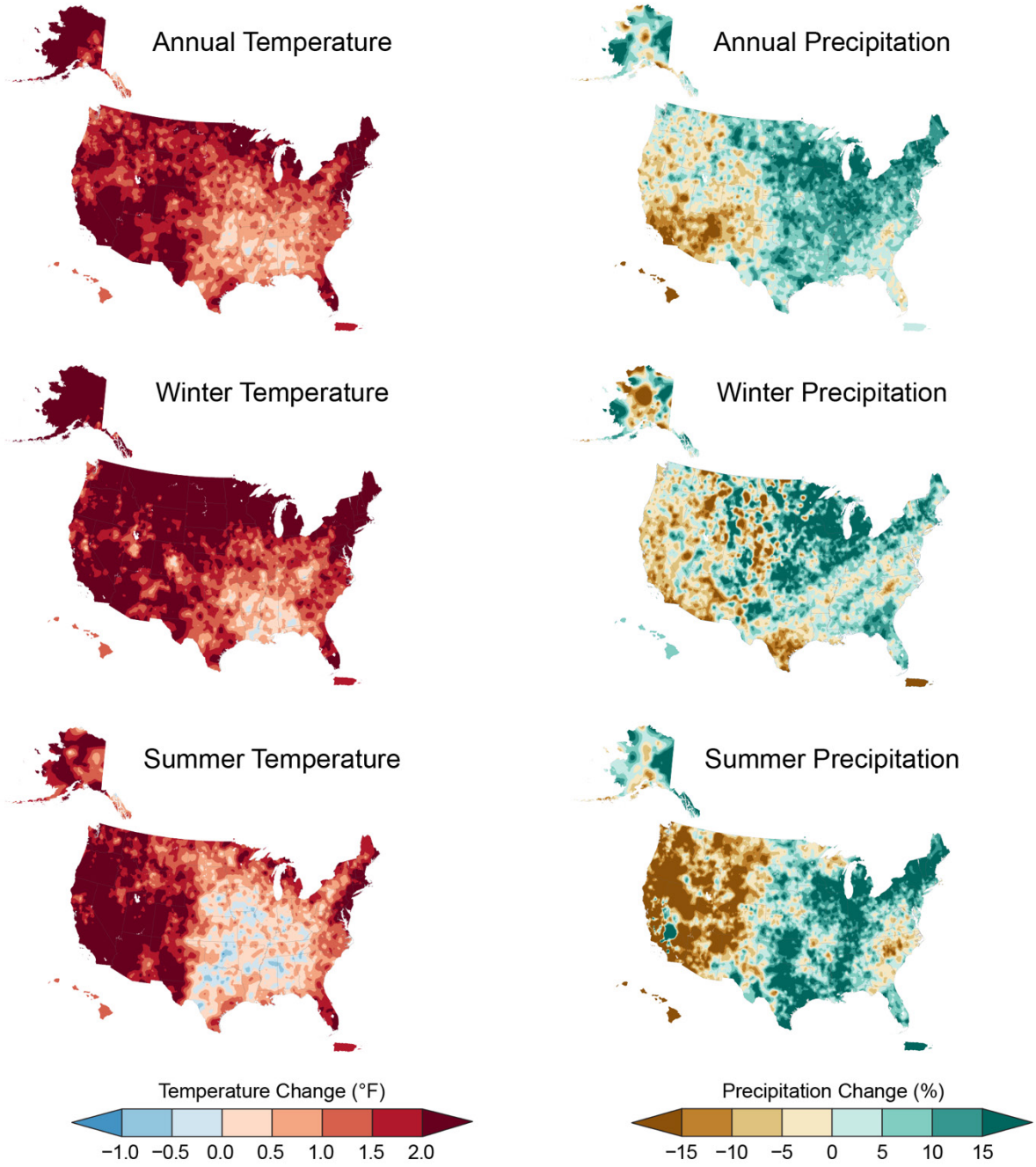
### The US Is Warming Faster Than the Global Average

Temperatures in the contiguous United States (CONUS) have risen by 2.5°F and temperatures in Alaska by 4.2°F since 1970, compared to a global temperature rise of around 1.7°F over the same period. This reflects a broader global pattern in which land is warming faster than the ocean, higher latitudes are warming faster than lower latitudes, and the Arctic is warming fastest of all.[50] There are substantial seasonal and regional variations in temperature trends across the US and its territories. Winter is warming nearly twice as fast as summer in many northern states (Figure 2.4). Annual average temperatures in some areas (including parts of the Southwest, upper Midwest, Alaska, and Northeast) are more than 2°F warmer than they were in the first half of the 20th century, while parts of the Southeast have warmed less than 1°F. These regional differences are most pronounced in the summer: seasonal temperatures in some regions east of the Rockies have decreased. Studies have linked these regional trends to a combination of natural climate variability,[51,52,53,54,55] human-caused drivers such as irrigation and agricultural intensification,[56,57] and aerosol pollution (Figure 2.4; Ch. 3).[53,58] This decreasing trend has recently reversed in the southeastern US, possibly in response to decreasing aerosol amounts (Figure 2.2),[59] a shift projected to increase climate change impacts in that region (Ch. 22).

### The Characteristics of Precipitation Are Changing

Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002–2021 was 5%–15% higher relative to the 1901–1960 average in the central and eastern US, a trend attributable to climate change.[60] Hawai'i (Ch. 30) and parts of the Southwest (Ch. 28) are getting drier (Figure 2.4), recording average annual precipitation decreases between 10% and 15% over the same time period. The timing of precipitation is also changing. While the Northeast and Midwest have seen wetter conditions in all seasons, the Southeast has received more precipitation in the fall but drier conditions in spring and summer.[61] Across most of the Southwest, precipitation was more than 15% below average during summer, fall, and spring and 10%–15% above average in the winter.[62,63] The Pacific Northwest also experienced drier summers and wetter winters. More precipitation is now falling as rain rather than snow, which is contributing to reductions in snowpack and maximum annual snow equivalent (Ch. 4; Figure A4.7).

## Observed Changes in Annual, Winter, and Summer Temperature and Precipitation




**Temperature has increased and precipitation has changed over much of the United States.**

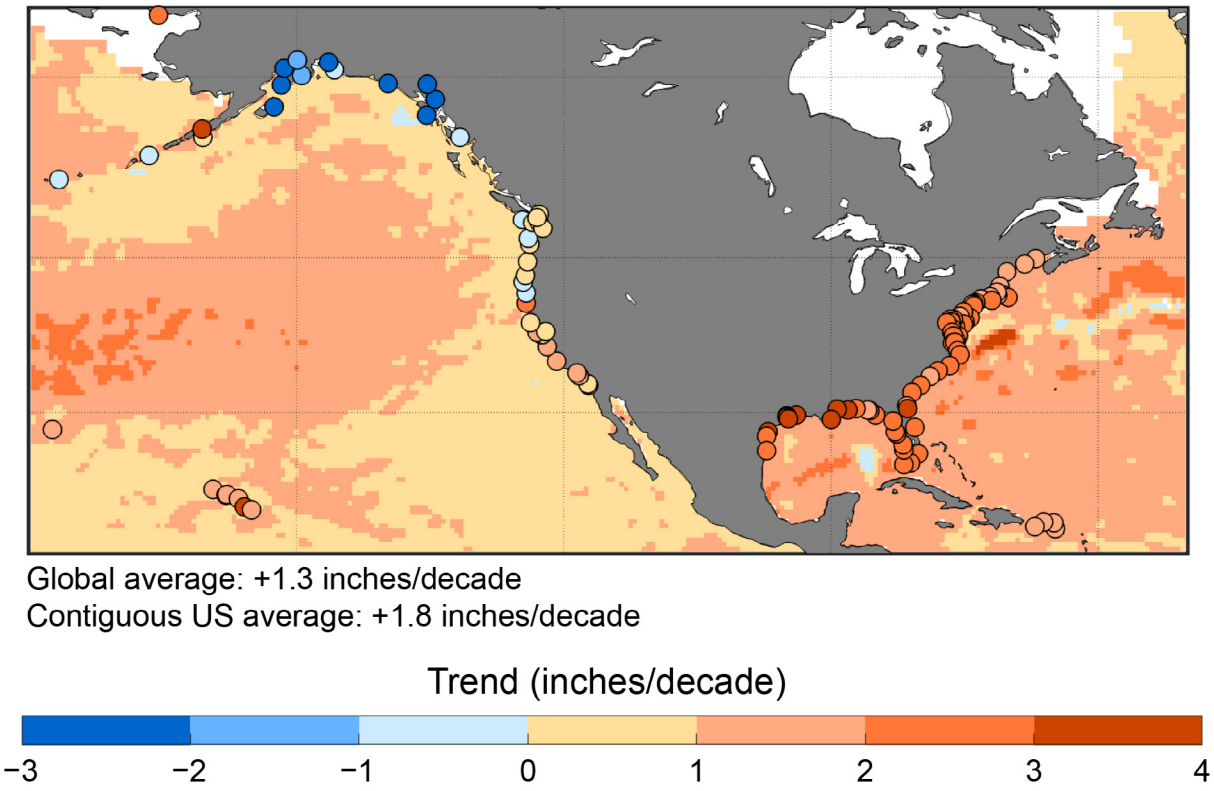
**Figure 2.4.** Changes shown are the difference between the annual average or seasonal temperatures (**left column**) and precipitation totals (**right column**) for the present day (2002–2021) compared to the average for the first half of the last century (1901–1960) for the contiguous United States (CONUS), Hawai'i, and Puerto Rico; and 1925–1960 for Alaska. Temperature and precipitation estimates for CONUS and Alaska are derived from the nClimGrid dataset.[64,65] For Hawai'i and Puerto Rico, temperature estimates are derived from NOAAGlobalTemp,[5] and precipitation estimates are derived from the Global Precipitation Climatology Center dataset.[66] Figure credit: NOAA NCEI and CISESS NC.

## Sea Level Along the Continental US Coast Is Rising Faster Than the Global Average

Over the past century, average sea level along the continental US coastline has risen by about 11 inches, which is considerably more than the global average sea level rise of 7 inches.[67] In just the last three decades (1993–2020), sea level has risen at a rate of 1.8 inches per decade in the continental US compared to 1.3 inches per decade globally (Figure 2.5). Over the same period, the rate of sea level rise has accelerated both globally and in the continental US.[68] Within the US, rates of relative sea level rise (i.e., changes in sea level relative to local land surface heights, including local changes in land elevation) vary spatially, with the highest rates between 1993 and 2020 observed along the Gulf and Mid-Atlantic Coasts (greater than 2.4 inches per decade of sea level rise, as shown in Figure 2.5), the lowest rates in the Pacific Northwest (0–1 inches per decade of sea level rise, as shown in Figure 2.5), and relative sea level fall in Southeast Alaska.

Many processes have contributed to these regional differences. Land subsidence has driven very high rates of relative sea level rise along the Gulf Coast. Variations in ocean circulation and land subsidence have driven higher rates of sea level rise along the Mid-Atlantic Coast over recent decades.[69,70] On the Pacific Coast, ocean-circulation variation related to the Pacific Decadal Oscillation and local land uplift have caused lower rates of sea level rise and, in some places (such as Southeast Alaska), even sea level fall.[71] Changes in average sea level have doubled the frequency of disruptive high tide flooding in the continental United States over the past few decades.[72] In some cities, the increase in flood frequency has been even greater due to locally higher rates of sea level rise—for example, a fourfold increase in the frequency of disruptive high tide flooding events in Miami Beach, Florida, over the last 20 years.[73]

## Observed Sea Level Trends




**Sea levels are rising across most US coastal areas.**

**Figure 2.5.** Satellite and tide gauge data show trends in sea level rise during 1993–2020 that are, on average, greater than global trends. Sea levels are not rising uniformly across US coastlines. The highest rates of sea level rise have occurred along the Gulf Coast and Atlantic Coast, with lower rates on the Pacific Coast and sea level fall along parts of the Alaska Coast. Rates of sea level rise in Hawai'i and Puerto Rico are closer to the global average. Adapted from Sweet et al. 2022.[67]

## Oceans Are Changing

The oceans are warming along all US coasts, but not all areas are warming at the same rate.[74,75] Surface waters along the Alaska and Northeast coastlines are warming faster than in most other regions due to climate change impacts on weather and ocean circulation in those regions (KMs 21.2, 29.5).[76] Oxygen minimum zones (areas of the deeper ocean where oxygen levels are low) have expanded in volume since 1970, particularly in Alaska waters, with negative consequences for fisheries (Ch. 10).[77,78,79] Dead zones—areas in the coastal ocean where oxygen levels seasonally drop, sometimes causing massive die-offs of marine life—are happening in more places around the country, with climate change one of many factors contributing to their expansion.[77,80] Acidification, caused by rising levels of atmospheric $CO_2$ being absorbed by the ocean (KM 3.4; Figure 3.9), has changed the carbonate chemistry of US offshore and coastal waters at variable rates, impacting marine life.[81] Acidification in offshore and open ocean waters tracks the global average trends,[1] but changes in US coastal waters depend on regional upwelling conditions (Ch. 27) and acidifying contributions from land and nutrient and freshwater inputs.[82,83]

### Sea and Lake Ice Is Decreasing

Sea ice has dramatically retreated from Alaska coastal seas over the last several decades at rates that exceed retreat in other parts of the Arctic Ocean (Ch. 29).[79,84] In 2018, sea ice in the Bering Sea of Alaska reached a record low at less than half the average winter extent since 1979.[85] Throughout North America and the Arctic, lake ice area and seasonal duration have also notably decreased during the satellite era (Ch. 24).[86,87]

## *Changes Outside National Borders Affect the United States*

### Warming in the Tropics Affects the Entire United States

Observed changes in atmospheric circulation are shifting the distribution of precipitation throughout the tropics and subtropics, resulting in greater precipitation variability for Caribbean and Pacific islands (Chs. 3, 23, 30).[88] These shifts are also thought to extend tropical cyclone tracks farther into the midlatitudes,[89] especially in the West Pacific basin. Tropical cyclone activity in the West Pacific has also been linked to an intensifying effect on the El Niño–Southern Oscillation (ENSO).[90,91,92] ENSO itself has tended toward more extreme events since the 1950s[93] that strongly impact the US-Affiliated Pacific Islands (Ch. 30) but also heavily influence temperature and precipitation patterns in several continental US regions,[94,95,96] as well as the development of tropical cyclones in the Pacific and Atlantic basins.[97] The tropics are also a key source of moisture for atmospheric rivers and tropical storms that bring precipitation to much of the country. As the tropics warm, the subsequent increase in moisture is intensifying the precipitation associated with these systems across the western and eastern United States.[98,99]

### Ice Sheet Changes in Greenland and Antarctica Contribute to US Sea Level Rise

The pattern of mass loss from glaciers and ice sheets outside the United States also has an important influence on the spatial pattern of sea level rise along US coasts, as ice losses in Antarctica lead to more sea level increase along the US Atlantic Coast than equivalent ice losses in Greenland, due to gravitational changes associated with the redistribution of mass on the Earth's surface.[100,101] Improved estimates of sea level changes during warm periods in Earth's prehistory are now directly being used to calibrate projections of the upper bound of future sea level rise.[102,103] The closest analog for current rates of sea level rise, and those that may occur in the next century, are past warm periods when the Greenland and Antarctic ice sheets were considerably smaller than their present state and global average sea level was 10 or more feet higher.[104]

### Arctic Changes Affect Weather in the Midlatitudes

The Arctic is warming faster than much of the world, and Arctic sea ice is declining rapidly as a consequence.[49] There is emerging evidence from modeling studies and observations that these changes in the Arctic are affecting atmospheric circulation and extreme weather across the United States. In summer, the temperature contrast between the Arctic and the midlatitudes has decreased, weakening the midlatitude jet stream and making certain weather regimes more persistent.[105] This has led to more persistent hot and dry extremes over parts of North America.[105,106,107] However, the connection between Arctic warming and winter weather is still uncertain. In winter, the influence of natural climate variability and the lack of consistency between observations and modeling-based studies make it difficult to connect changes occurring in the Arctic and winter severe weather.[108,109] However, some recent studies suggest that Arctic warming results in increasing disruptions of the stratospheric polar vortex that cause cold air from the Arctic to spill down over the United States, as seen in recent severe winter weather events such as the February 2021 cold snap that affected large parts of the country (Figure 26.7).[110,111,112] Notably, this Arctic air, while still cold in absolute terms, is warmer than it used to be four decades ago.

## Key Message 2.2

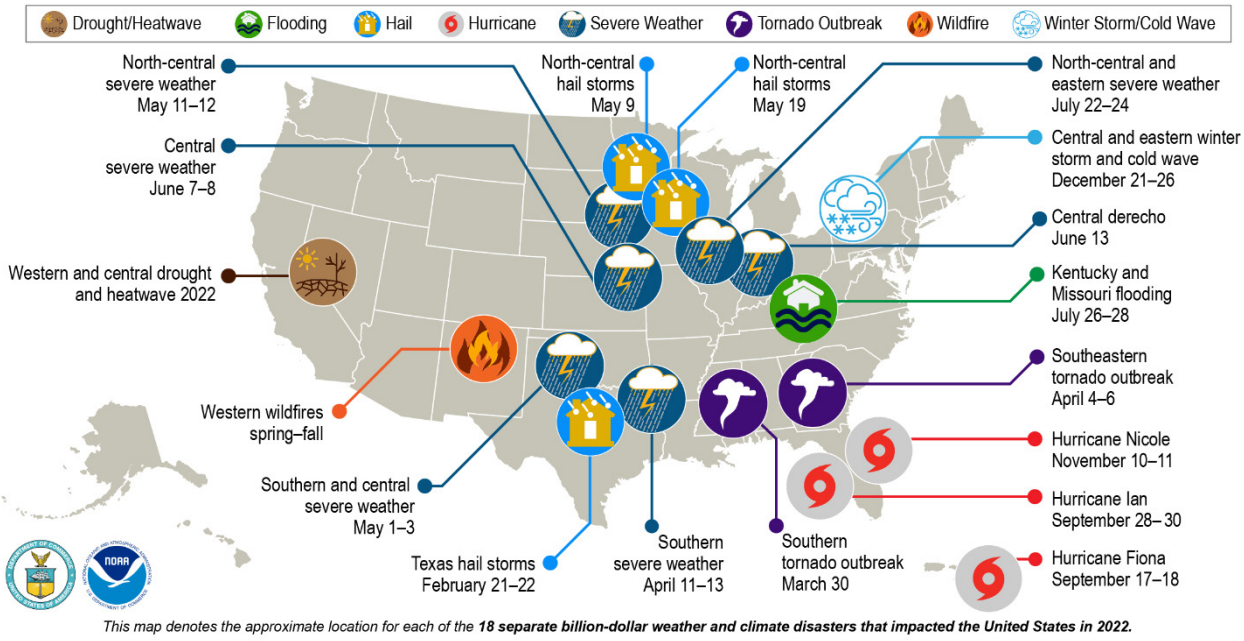
## Extreme Events Are Becoming More Frequent and Severe

Observations show an increase in the severity, extent, and/or frequency of multiple types of extreme events. Heatwaves have become more common and severe in the West since the 1980s (*high confidence*). Drought risk has been increasing in the Southwest over the past century (*very high confidence*), while at the same time rainfall has become more extreme in recent decades, especially east of the Rockies (*very high confidence*). Hurricanes have been intensifying more rapidly since the 1980s (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*). More frequent and larger wildfires have been burning in the West in the past few decades due to a combination of climate factors, societal changes, and policies (*very high confidence*).

### *Climate Change Is Not Just a Problem for Future Generations, It's a Problem Today*

The number and cost of weather-related disasters have increased dramatically over the past four decades, in part due to the increasing frequency and severity of extreme events and in part due to increases in exposure and vulnerability. In 2022 alone, the United States experienced 18 weather and climate disasters with damages exceeding $1 billion (Figures 2.6, A4.5). There is increasing confidence that changes in some extreme events are driven by human-caused climate change (KM 3.5).

## Billion-Dollar Weather and Climate Disasters in 2022



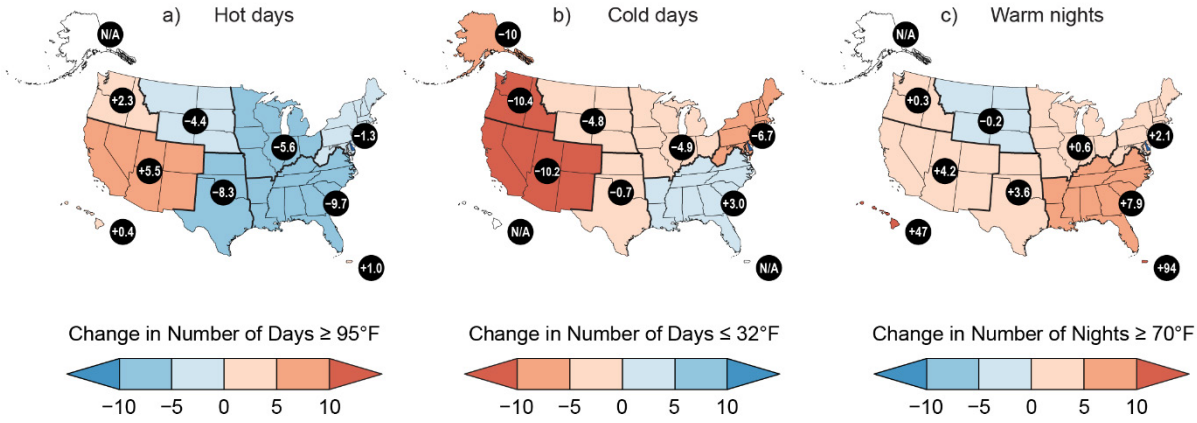

**The US experienced 18 billion-dollar weather and climate disasters in 2022.**

**Figure 2.6.** In the 1980s, there was one weather/climate disaster event with losses exceeding $1 billion approximately every four months. By the 2010s, there was one every three weeks or less. In 2022, there were 18 such events that affected the United States. These events included 1 drought event, 1 flooding event, 11 severe storm events (including tornadoes, hail storms, and straight-line winds), 3 tropical cyclone events, 1 wildfire event, and 1 winter storm event. Overall, these events resulted in the deaths of 474 people and had significant economic effects on the areas impacted. Source: NCEI 2022.[15]

## The Risk of Temperature Extremes Is Changing

By some measures, the most extreme heatwaves on record in the United States occurred during the Dust Bowl era of the 1930s.[113] This serves as a historical reminder of the societal consequences of extreme heat. Globally, such heatwaves are becoming more frequent, and in recent decades the western United States has been following those trends. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021. The western US has been particularly affected by extreme heat since the 1980s (Figure 2.7), experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US.[114] By contrast, the number of very hot days has actually decreased across the central and eastern regions due to summer cooling trends in the region (Figure 2.7; Ch. 22). This does not, however, mean the central and eastern US are not affected by heat. The impacts of extreme high temperatures are more severe if such conditions persist for several days, and overall, multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades.[115,116,117] Across 50 large US cities, the US Global Change Research Program heatwave indicator (https://www.globalchange.gov/indicators/heat-waves) shows that the average number of heatwaves has doubled since the 1980s, and the length of the heatwave season has increased from about 40 days to about 70 days.[118] Even the ocean is experiencing extreme heat: marine heatwaves—prolonged periods of discrete (from days to several months) anomalously high sea surface temperatures—have now been documented in every US marine system (KMs 8.2, 10.1, 21.2, 27.2, 28.2, 30.4; Box 10.1; Figure 29.1).[119]

## Observed Changes in Hot and Cold Extremes




**Hot days have increased in the West, hot nights have increased nearly everywhere, and cold days have decreased.**

**Figure 2.7.** Over much of the country, the risk of warm nights has increased while the risk of cold days has decreased. The risk of hot days has also increased across the western US. This figure shows the observed change in the number of (**a**) hot days (days at or above 95°F), (**b**) cold days (days at or below 32°F), and (**c**) warm nights (nights at or above 70°F) over the period 2002–2021 relative to 1901–1960 (1951–1980 for Alaska and Hawai'i and 1956–1980 for Puerto Rico). Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credit: Project Drawdown, Washington State University Vancouver, NOAA NCEI, and CISESS NC.

The number of cold days (on which the temperature drops below freezing) has decreased across CONUS (except in the Southeast, where the number of days below freezing is small to begin with). Despite some recent damaging cold events, overall cold extremes are becoming less frequent and milder (Figure 2.7).[120,121]

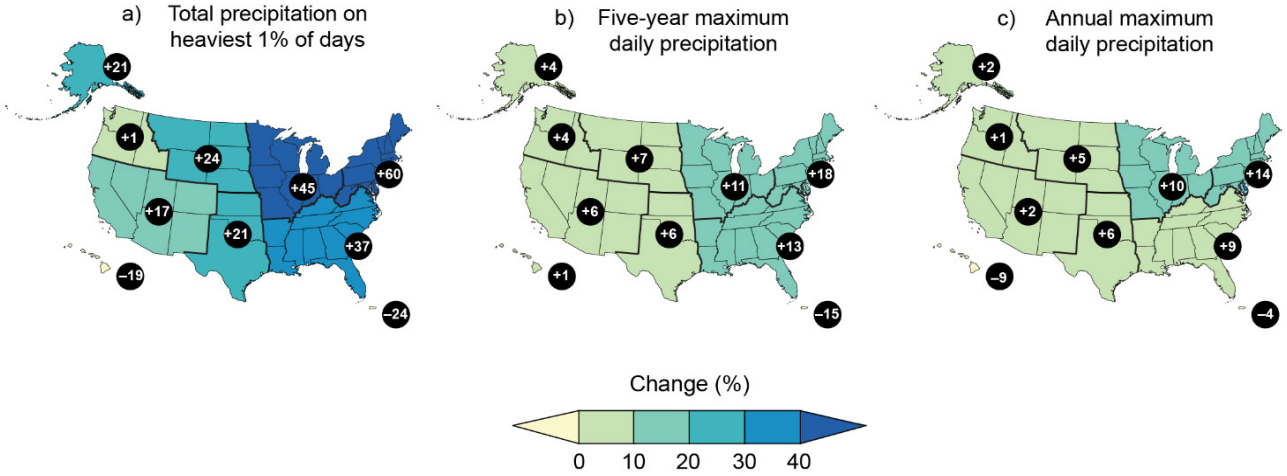
Nighttime temperatures are rising faster than daytime temperatures, and the number of nights where the temperature never falls below 70°F is increasing everywhere in the US except the Northern Great Plains (Figure 2.7). The extent of CONUS experiencing hot summer nights is growing at a faster rate than the extent experiencing hot summer days.[121,122] Temperatures are generally lower at night, allowing human (and animal) bodies, crops, and the built environment to cool down. For that reason, an increase in the frequency and intensity of warm nights can have a significant impact on human health, crop yields, and more.

## Rainfall Is Becoming More Extreme

Since the 1950s, there has been an upward trend in heavy precipitation across the contiguous US (Figure 2.8).[25] This increase is driven largely by more frequent precipitation extremes, with relatively smaller changes in their intensity. The largest increase in the number of extreme precipitation days (defined as the top 1% of heaviest precipitation events) has occurred over the Northeast (an increase of around 60%) and Midwest (around 45%), along with increases of more than 10% in their annual and 5-year maximum amount (Figure 2.8). These changes have contributed to increases in river and stream flooding in these regions.[123,124] The increase in frequency and intensity of precipitation extremes is evident across a broad range of event durations (from 1 to 30 days) and return intervals (1 to 20 years), particularly east of the Rocky Mountains.[125]

There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.[126,127] Paleoclimate records derived from tree-ring growth provide evidence that summer moisture has increased over the past century in parts of New England,[128] the central-eastern US,[129] and the northern Mississippi River valley.[130]

## Observed Changes in the Frequency and Severity of Heavy Precipitation Events




**Heavy precipitation events are becoming more frequent and intense across much of the country.**

**Figure 2.8.** The frequency and intensity of heavy precipitation events have increased across much of the United States, particularly the eastern part of the continental US, with implications for flood risk and infrastructure planning. Maps show observed changes in three measures of extreme precipitation: (**a**) total precipitation falling on the heaviest 1% of days, (**b**) daily maximum precipitation in a 5-year period, and (**c**) the annual heaviest daily precipitation amount over 1958–2021. Numbers in black circles depict percent changes at the regional level. Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credits: (a) adapted from Easterling et al. 2017;[131] (b, c) NOAA NCEI and CISESS NC.

## Drought Risk Is Complex and Changing

Drought is such a complex phenomenon that it is a challenge to even define what it is: more than 150 different definitions have appeared in the scientific literature.[132] Broadly, drought results when there is a mismatch between moisture supply and demand. Meteorological drought happens when there is a severe or ongoing lack of precipitation. Hydrological drought results from deficits in surface runoff and subsurface moisture supply. Drying soil moisture affects crop yields and can lead to agricultural droughts. The timing of droughts is also complex. Droughts can last for weeks or decades. They may develop slowly over months or come on rapidly. A drought may be immediately apparent or detectable only in retrospect.

Despite this complexity, some robust regional trends are emerging. Colorado River streamflow over the period 2000–2014 was 19% lower than the 20th-century average,[133] largely due to a reduction in snowfall, less reflected sunlight, and increased evaporation.[134] The period 2000–2021 in the Southwest had the driest soil moisture of any period of the same length in at least the past 1,200 years.[135] While this drought is partially linked to natural climate variability, there is evidence that climate change exacerbated it, because warmer temperatures increase atmospheric "thirst" and dry the soil.[24,136,137,138] Droughts in the region are lasting longer[139] and reflect not a temporary extreme event but a long-term aridification trend—a drier "new normal"[140] occasionally punctuated by periods of extreme wetness consistent with expected increases in precipitation volatility in a warming world.[141,142]

The Southwest is the only region in which the total area of unusually dry soil moisture is increasing.[143] In the eastern regions of the country, hydrological droughts have become less frequent since the late 19th century due to increases in precipitation that compensate for warming-driven increases in evaporation (Figures 2.4, A4.9).[144] However, there is evidence that the likelihood of drought in the Northeast did not decrease as much as would be expected given these wetter conditions[145] and that higher increases in evapotranspiration make the Southeast more drought-prone than the Northeast (Ch. 22). Additionally, much of the US is

vulnerable to rapid-onset flash droughts that can materialize in a matter of days, driven by extreme high temperatures or wind speeds and a lack of rainfall.[146,147] These events are difficult to predict and prepare for, and can have outsized impacts.[148] There is evidence that these events are drying out soil more quickly as the world warms.[149]

## Storms Are Changing

Changes in some types of storms are also apparent. Over the past three decades, heavy snowfalls have been more frequent over the Northeast,[111] a trend consistent with warming in the western Atlantic Ocean and increasingly frequent Arctic air outbreaks from polar vortex disruptions.[110] Atmospheric rivers along the Pacific Coast have become warmer over the past several decades[150] and have transported larger amounts of moisture into the West because of increases in Pacific Ocean temperatures.[151]

There is no long-term trend in the frequency of landfalling hurricanes in the United States since the late 19th century, but there has been an increase in basin-wide hurricane activity in the North Atlantic since the early 1970s.[152,153] In addition to recent increases in storm frequency, evidence continues to build that hurricanes are changing in other dangerous ways. Tropical cyclones have been intensifying more rapidly since the early 1980s,[154,155] leaving communities with less time to prepare. Hurricanes tend to lose energy as they move away from the ocean, but the rate of this hurricane decay has slowed since the 1960s, allowing storms to extend somewhat farther inland.[156] There has been a 17% decrease in the speed of movement of storms in the North Atlantic basin since 1900,[157] as well an increased tendency for storms along the North American coast to meander and stall since the 1950s.[158] Slower-moving storms can result in more heavy rainfall, wind damage, storm surge, and coastal flooding; notably, after accounting for changes in the value of property and other assets placed in harm's way, hurricane damage in the United States has generally increased since 1900.[159]

Changes in smaller-scale, short-lived severe weather such as tornadoes and thunderstorms are more difficult to assess, and direct observations of those events and the conditions associated with them are incomplete.[160] While the average annual number of tornadoes appears to have remained relatively constant, there is evidence that tornado outbreaks have become more frequent,[161] that tornado power has increased,[162] that tornado activity is increasing in the fall,[163] and that "Tornado Alley" has shifted eastward.[164] The complexes of thunderstorms that bring substantial precipitation to the central United States during the warm season have become more frequent and longer-lasting over the past two decades.[165]

Thunderstorms are associated with other important hazards, including hail and cloud-to-ground lightning. Direct observational records for these hazards are largely insufficient for identifying trends due to factors including observer biases, limited length of the record, and changes in the observing systems.[166,167] However, days with environmental conditions conducive to producing large hail (greater than 2 inches in diameter) have become more frequent over the central and eastern US and parts of the Pacific Northwest.[168]

## A Combination of Factors Is Increasing Fire Risk

Much of the country is experiencing more intense and frequent wildfires associated with warming and drought[16,169] and aggravated by the reduction in Indigenous land-use and fire stewardship practices that have been critical for past management of fires.[170,171] Over the past 1,000 years, warm temperatures and droughts have tended to increase the area burned by wildfires in the West, including the Pacific Northwest and Rockies.[172] In the period 1979–2020, human-caused warming was responsible for nearly 68% of the observed increase in aridity in the West, creating the conditions that drove growth in the acreage burned by wildfires.[173] In the Rockies, higher temperatures, changes in precipitation, and fire stress have led to major ecological changes, including the disappearance of forests (Ch. 7).[174] Fire history records derived from tree rings and fire scars from forests in the Rocky Mountains show that for most of the past 2,000 years, cooler, wetter conditions, combined with Indigenous fire stewardship practices, limited fires.[171] However,

greenhouse gas–induced warming and drying and the spread of invasive vegetation types (KM 8.2) have combined with forest management policy choices and the limitation of Indigenous sovereignty to contribute to new extreme fire regimes and more frequent fires.

Lightning and human activities are both sources of wildfire ignitions in the US. Lightning is a dominant source across much of the western US and is associated with larger and more intense fires, while humans are a dominant source across the eastern US and along the Southern California coastline.[167,175,176] Both lightning-caused and human-caused fires have increased between 1992 and 2012.[175] While rising populations, development, and a growing wildland–urban interface contribute to the increase in human-caused fires,[177] there is no clear evidence of changes in lightning activity.[178,179] Changes in lightning activity are challenging to detect due to the lack of long-term satellite measurements and uncertainties in ground-based lightning detection networks.[167]

## Key Message 2.3

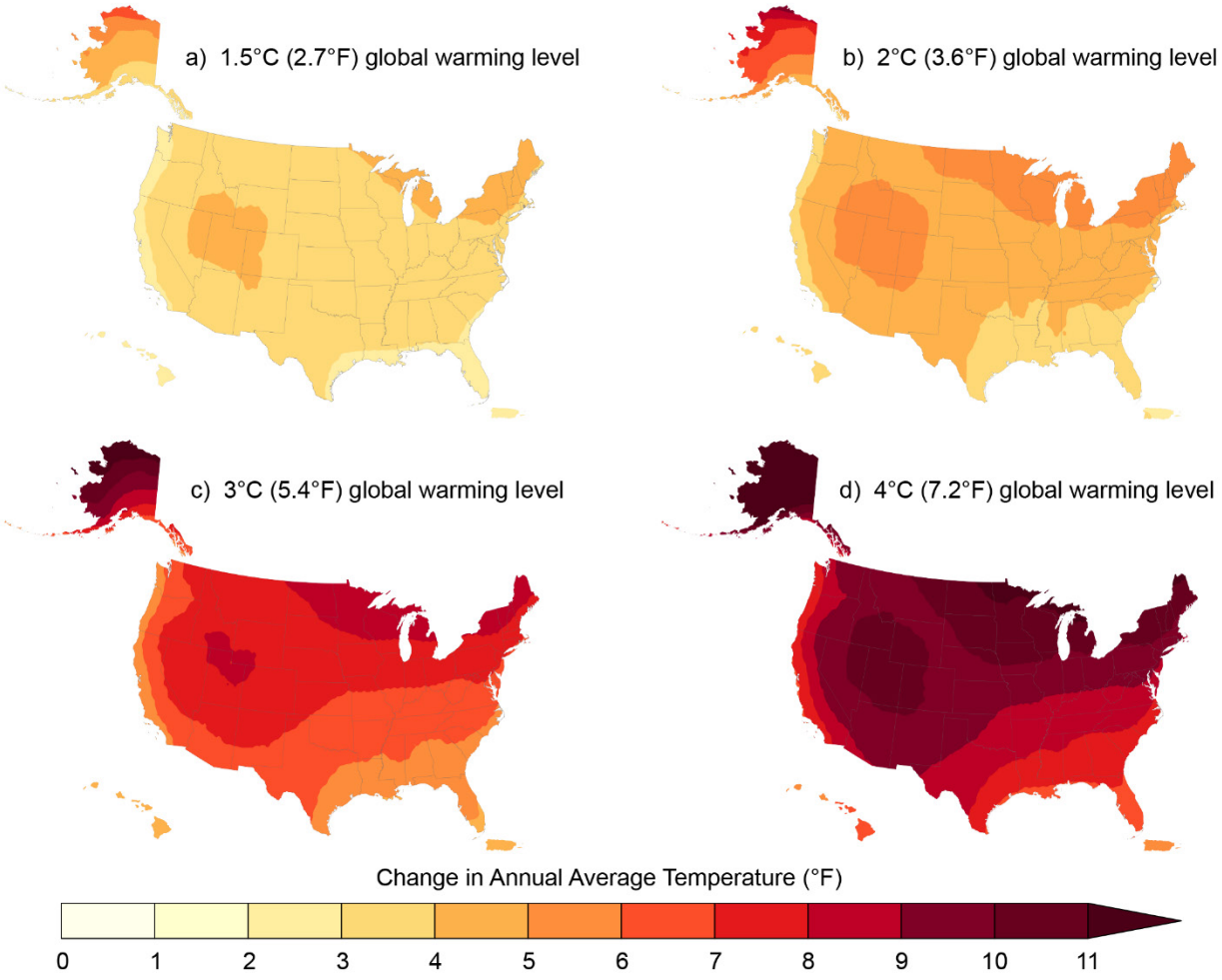
## How Much the Climate Changes Depends on the Choices Made Now

The more the planet warms, the greater the impacts—and the greater the risk of unforeseen consequences (*very high confidence*). The impacts of climate change increase with warming, and warming is *virtually certain* to continue if emissions of carbon dioxide do not reach net zero (*very high confidence*). Rapidly reducing emissions would *very likely* limit future warming (*very high confidence*) and the associated increases in many risks (*high confidence*). While there are still uncertainties about how the planet will react to rapid warming and catastrophic future scenarios that cannot be ruled out, the future is largely in human hands.

### *As the World Warms, the United States Warms More*

Every increment of global warming leads to larger increases in temperature in many regions, including much of the United States (Figure 2.9). The Paris Agreement calls for limiting global warming to "well below 2°C" relative to preindustrial temperatures, preferably to 1.5°C, and domestic and international emissions targets are generally expressed in these terms. To mirror this language, where possible, trends in this section are reported in terms of the global warming level (GWL): the global average temperature change in degrees Celsius relative to preindustrial temperatures. At a GWL of 2°C (3.6°F), the average temperature across the United States is *very likely* to increase between 4.4°F and 5.6°F (2.4°C and 3.1°C). For every additional 1°C of global warming, the average US temperature is projected to increase by around 2.5°F (1.4 °C). The northern and western parts of the country are *likely* to experience proportionally greater warming (Figure 2.9).

### Projected US Temperature Changes at 1.5°C, 2°C, 3°C, and 4°C of Global Warming



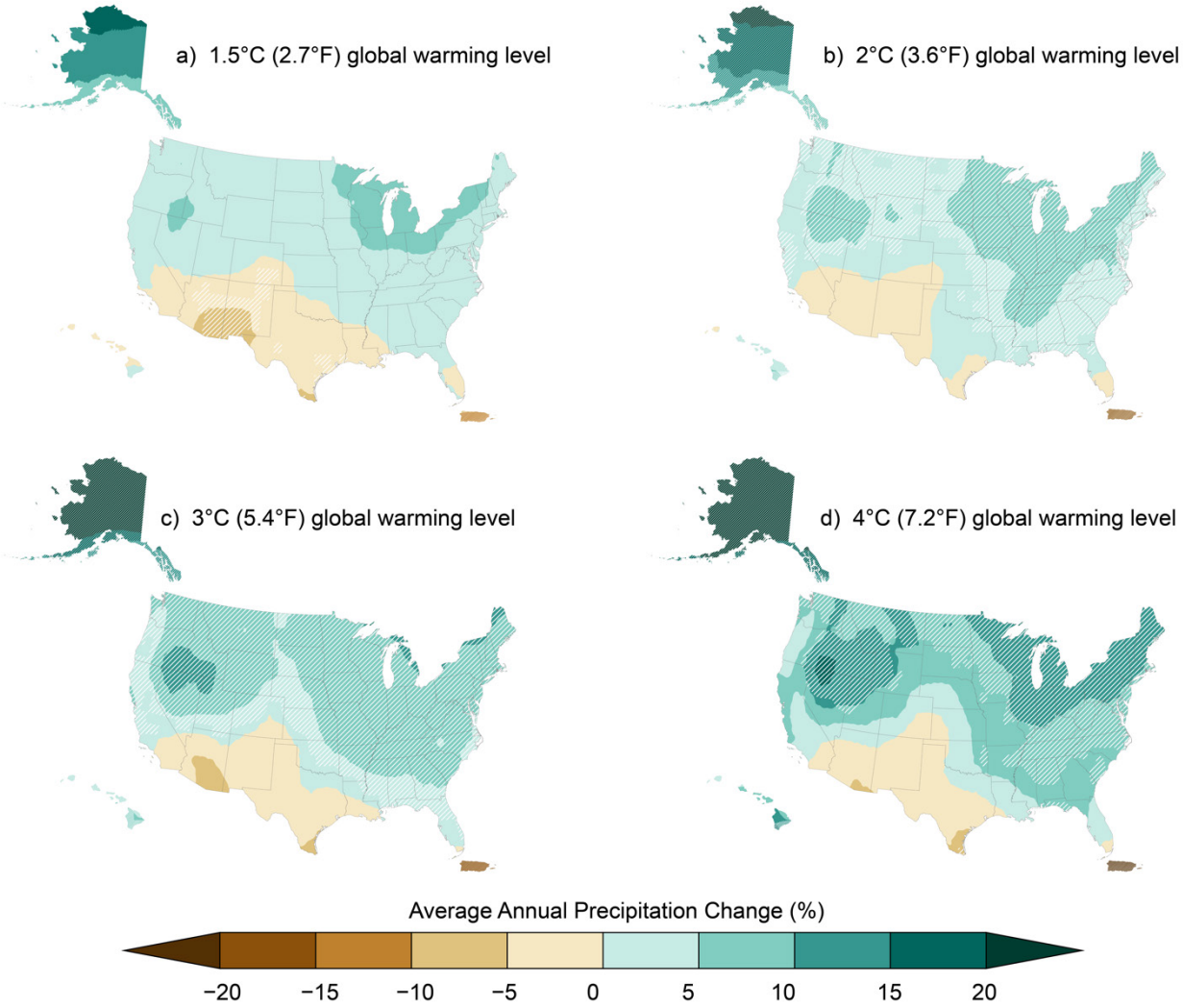

**The United States is projected to warm faster than the global average.**

**Figure 2.9.** As the world warms, the US warms more. Projected temperature rises are larger in the northern and western portions of the country and are most severe in the Arctic. These maps show projected changes in annual average temperature (°F) for various global warming levels (1.5°, 2.0°, 3.0°, and 4.0°C). Changes are relative to the period 1851–1900. Based on CMIP6. Data were not available for the US-Affiliated Pacific Islands. Figure credit: NOAA NCEI and CISESS NC.

## *Some Regions Will Get Wetter While Others Will Get Drier*

Precipitation changes also scale with global warming, but these projections vary by location (Figure 2.10) and are less certain than temperature changes. As global temperatures increase, annual average precipitation is *very likely* to increase in the northern and eastern regions of CONUS and in Alaska, more likely than not to decrease in the Southwest and Texas, and *likely* to decrease in the Caribbean. Changes to the seasonal cycle of precipitation are also expected: in the Northwest, precipitation increases are *very likely* to occur during the winter wet season and decrease in the summer. In a warmer world, it is *virtually certain* that less precipitation will fall as snow, leading to large reductions in mountain snowpack and decreases in spring runoff in the mountain West (Chs. 4, 27, 28; Figure A4.7).

## Projected US Precipitation Changes at 1.5°C, 2°C, 3°C, and 4°C of Global Warming



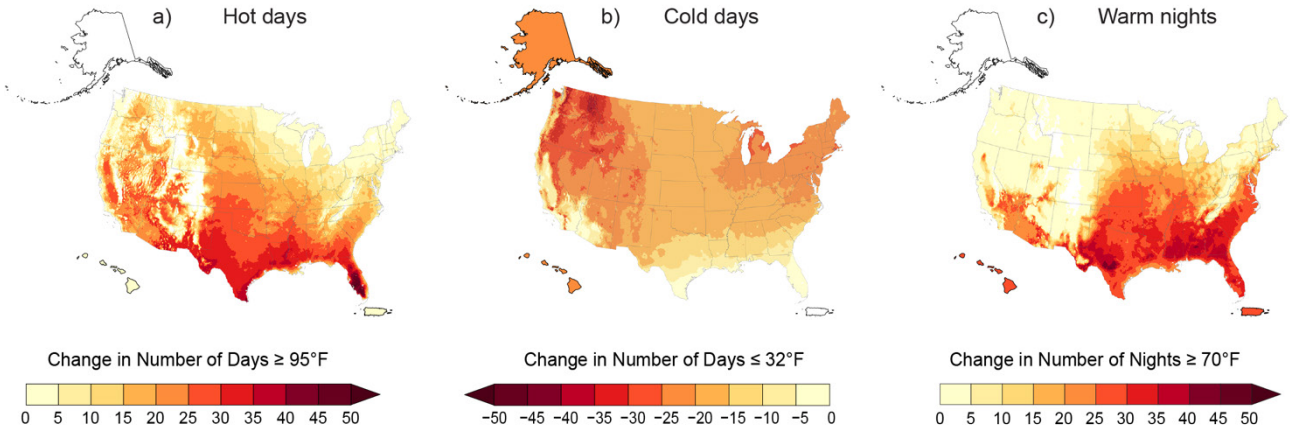

**Precipitation changes are projected to be larger at higher levels of warming.**

**Figure 2.10.** These maps show projected changes in average annual precipitation (%) for various global warming levels (1.5°, 2.0°, 3.0°, and 4.0°C). Precipitation is projected to increase with warming in the North and East and to decrease in the Southwest and the Caribbean. Changes are relative to the period 1851–1900. Based on CMIP6. Data were not available for the US Affiliated Pacific Islands. Hatching indicates areas where 80% or more of the models agree on the sign of the change. Figure credit: Project Drawdown, Stripe Inc., NOAA NCEI, and CISESS NC.

## The Risk of Extreme Heat Increases with the Global Warming Level

Recent trends in extreme heat and precipitation foreshadow what is to come in a warmer world. The connection between warming and heatwaves is well understood: at the very basic level, as average temperatures warm, the risk of extreme temperatures and record-breaking temperatures goes up (Ch. 3), and it is *very likely* that heatwaves will increase in frequency, severity, and duration as warming continues. Figure 2.11a shows projected changes in the number of days at or above 95°F at a global warming level of 2°C. In addition to changes in the number of hot days, multiday heatwaves are *very likely* to last longer, affect a larger spatial extent, and become more severe, exposing more people and infrastructure simultaneously and for longer periods.[180] By contrast, the number of cold days is projected to decrease (Figure 2.11b). Nighttime temperatures are *very likely* to increase faster than daytime temperatures, leading to an increase in extreme nighttime temperatures as the global warming level increases (Figure 2.11c). Such changes in extreme heat are *very likely* to have negative impacts on human health (Ch. 15) and agricultural productivity (Ch. 11).

### Projected Changes to Hot and Cold Extremes at 2°C of Global Warming



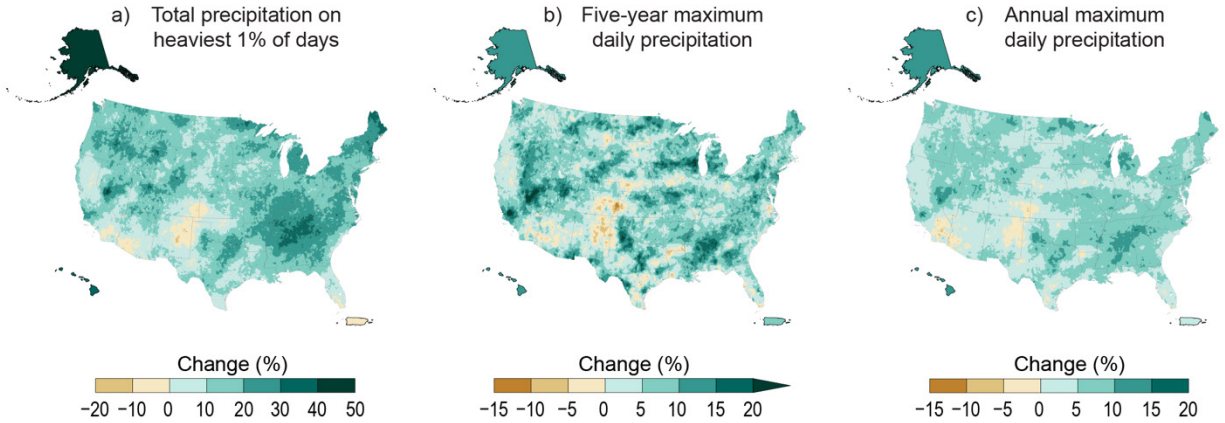

**More hot days, even more warm nights, and fewer cold days are expected at a global warming level of 2°C.**

**Figure 2.11.** These maps show changes in the (**a**) projected number of hot days with a maximum temperature at or above 95°F, (**b**) cold days (minimum temperature at or below 32°F), and (**c**) warm nights (minimum temperature at or above 70°F) at a global warming level of 2.0°C. Changes are relative to the period 1991–2020. Based on LOCA2/STAR. Values for Alaska, Hawai'i, and Puerto Rico are averages from STAR downscaling of 44, 15, and 31 stations, respectively. The Hawai'i value for cold days is for Mauna Loa, the only network station where freezing temperatures occur. Areas of no change (shown in white) generally will not experience temperatures exceeding those thresholds. Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credit: NOAA NCEI and CISESS NC.

## The Frequency and Severity of Heavy Precipitation Increases with the Global Warming Level

Extreme precipitation–producing weather systems ranging from tropical cyclones to atmospheric rivers are *very likely* to produce heavier precipitation at higher global warming levels.[127,181,182,183,184] Recent increases in the frequency, severity, and amount of extreme precipitation are expected to continue across the US even if global warming is limited to Paris Agreement targets.[126,185] Figure 2.12 shows *likely* changes at a GWL of 2°C. Changes in extreme precipitation events differ seasonally—they are *very likely* to increase in spring and winter across CONUS and Alaska and in eastern and northwestern states in the fall, while projected changes in the summer season are more uncertain.[186]

## Projected Changes to Precipitation Extremes at 2°C of Global Warming




**Increases in the frequency and severity of heavy precipitation are expected at a global warming level of 2°C.**

**Figure 2.12.** The maps show projected changes in three measures of extreme precipitation at a global warming level of 2°C: (**a**) total precipitation falling on the heaviest 1% of days, (**b**) daily maximum precipitation in a 5-year period, and (**c**) the annual heaviest daily precipitation amount. Changes are relative to the period 1991–2020. Based on LOCA2/STAR. Values for Alaska, Hawai'i, and Puerto Rico are averages from STAR downscaling of 45, 16, and 31 stations, respectively. Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credit: NOAA NCEI and CISESS NC.

## *Warming-Driven Changes to the Water Balance Affect Drought Risk*

Even as downpours increase, the risk of drought is also projected to rise with the global temperature. The past may provide insight into what could happen as temperatures rise. Paleoclimate datasets show that the already-water-stressed Great Basin region, which includes Nevada, parts of Utah and Wyoming, and much of the Southwest, experienced severe drought throughout the mid-Holocene (approximately 5,000–9,000 years ago), when the western Pacific was warm, Arctic temperatures were high, and there was less sea ice—all global changes that are projected in a future warmer world.[187] In the Southwest, multidecadal soil moisture droughts analogous to or drier than the 2000–2021 drought are projected to increase in the future, regardless of global warming level (Ch. 28).[188] This is due to projected decreases in springtime precipitation and earlier snowmelt that, combined with warmer temperatures, push the region into a new and drier average state.[140] However, the risk of single-year droughts analogous to the driest recent year (2002) depends strongly on the global warming level, increasing by 8% at a GWL of 2°C but by 24% at 4°C.[188] Limiting global warming would also reduce the severity of inevitable multidecadal droughts by reducing the magnitude of extreme single-year droughts during these events.

Other regions of the country are not projected to aridify to the same extent as the Southwest. However, projected changes in the amount, type, and timing of precipitation and evapotranspiration will affect the balance of water supply and demand, shaping drought risk in a warmer world. Springtime runoff from snowmelt is projected to decrease with warming in the northern and western regions of CONUS.[189] In the southern and eastern regions of the country, projected increases in winter and spring precipitation will increase moisture availability at the time soils are wettest, leading to higher runoff and flooding risk.[138] Drying of surface soils is projected to occur nearly everywhere; drying increases with the GWL due to increases in evaporative demand with warming. Deeper soil moisture projections are more uncertain,[190] but it is *likely* that total column soil moisture in the Southwest and parts of the Southern Great Plains will become drier with warming.[138]

## As the Planet Warms, Storms Become More Dangerous

There is increasing evidence that a warming planet will alter the characteristics and impacts of several storm types. With every increment of global warming, projected sea level rise is *very likely* to lead to higher storm inundation levels when storms do occur (Ch. 9). Projected increases in atmospheric water vapor are *very likely* to lead to more extreme rainfall rates (Ch. 3). Projected increases in water temperatures are *very likely* to result in stronger tropical cyclones globally, with winds 5% faster (3% for the Atlantic basin) at a GWL of 2°C. It is *likely* that the overall global frequency of tropical cyclones will decrease, while the frequency of Category 4–5 hurricanes is *likely* to increase.[183] Recent research points to continued uncertainty in the future frequency of Atlantic hurricanes (e.g., Sena et al. 2022;[191] Knutson et al. 2022[192]), landfall behavior, (e.g., Zhang et al. 2020;[193] Jing et al. 2021;[194] Knutson et al. 2022[192]) and associated hazards (e.g., Gori et al. 2022[195]), as well as possible shifts to increased tropical cyclone activity in the Central Pacific (Ch. 30).[192]

Even in regions that experience an overall decrease in precipitation, atmospheric rivers are projected to become stronger and wider,[184,196] increasing the risk of downpours and floods across the western United States.[181,184,197,198] In addition, the paleoclimate record shows that the locations along the Pacific Coast where storms bring moisture may also shift with warming.[199]

It is *likely* that the frequency of weather environments that give rise to severe thunderstorms in the United States during spring and fall will increase under stronger warming scenarios.[200,201] These changes are *likely* to lengthen the severe thunderstorm season as the world warms, especially in the Midwest and Southeast during cool-season months.[202]

## Warming Increases the Risk of Compound Extreme Events

The increasing risk of many individual extreme weather and climate events with warming also increases the risk that multiple extreme events may occur in quick succession in the same region. Warming also increases the risk of multiple extremes occurring simultaneously across multiple regions that are interconnected or interdependent (Focus on Compound Events). Co-occurring hot and dry conditions are projected to become more frequent with warming.[156,203,204] These conditions increase the risk of extreme wildfires, as well as affecting agriculture, water resources, and freshwater and marine ecosystems.

Co-occurring hot and moist conditions are also projected to increase with warming, and the risk of single and multiday humid-heat heatwaves across the densely populated Northeast, Southeast, and parts of the Southwest are projected to increase.[205] Higher temperatures combined with rising humidity due to the increased atmospheric moisture content are contributing to increases in humid-heat extremes—conditions that limit the ability of the human body to naturally cool down that are associated with reduced labor productivity and compounding heat-related health impacts.[206,207]

The combination of increasing drought risk and extreme precipitation are *likely* to increase the risk of extreme wildfire seasons that are followed shortly thereafter by heavy precipitation across the West,[208] which could increase the risk of postfire hazards such as debris flows, landslides, and flash floods similar to those that have affected parts of the region in recent decades (Ch. 4; Figure 3.13). The largest increases are expected in the Pacific Northwest, where this risk has historically been low.[208] Increases in hydroclimate volatility may also affect the Caribbean, Hawai'i, and some Pacific Islands (Chs. 23, 30). As global temperatures increase, the Atlantic and Gulf Coasts are projected to experience increases in compound flooding from rising sea levels that cause higher storm surge from stronger storms and heavier precipitation that result in runoff and flooding, impacting people, ecosystems, and infrastructure along the coastlines (Ch. 9).[195,209] The scientific understanding of such events continues to evolve (Focus on Compound Events).

## Warming Causes Long-Term Sea Level Rise

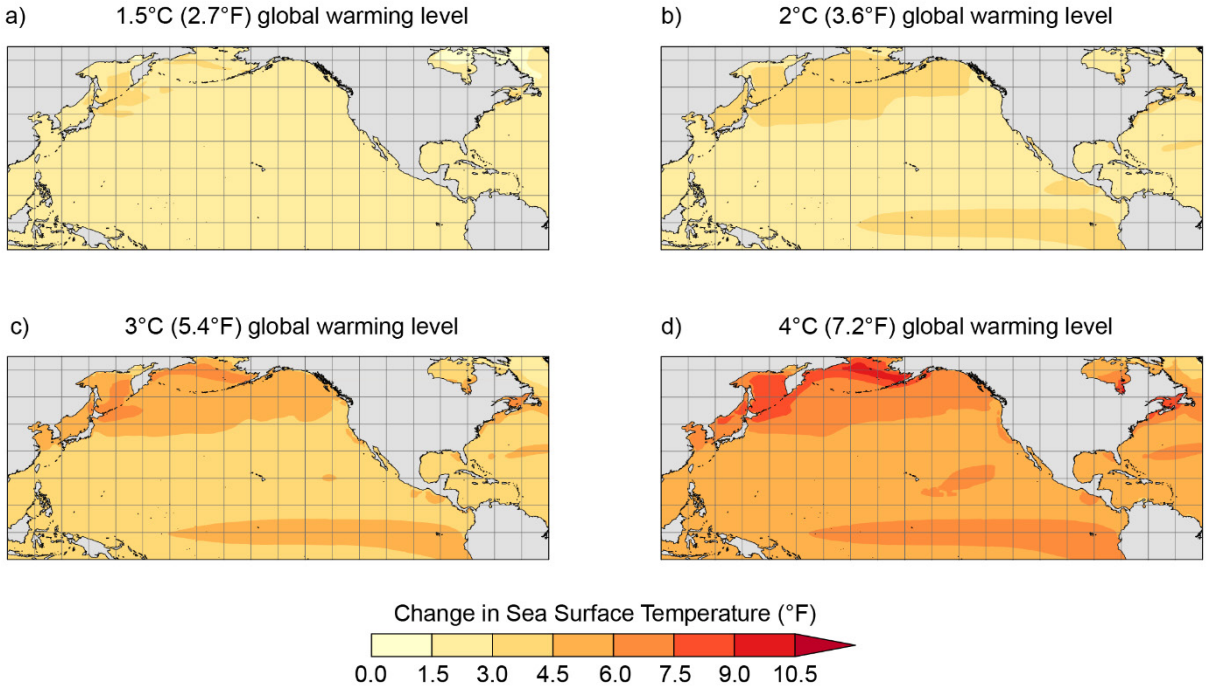
The most substantial differences in projected sea level rise for the United States for different global warming levels begin to arise at the end of this century, due to uncertainty in how much and how quickly ice will be lost from the Antarctic ice sheet.[210,211] A GWL of 2°C would lead to a *likely* sea level rise in CONUS of 2–3 feet in 2100 and 2.5–5 feet in 2150, relative to 2000 sea levels. Every additional degree Celsius of global warming is *likely* to cause at least 4 inches of additional sea level rise in CONUS in 2100 and at least 7 inches of additional sea level rise in 2150 (see Ch. 9 and Figure 9.2 for sea level projections in terms of global warming levels).[67] At a 2°C GWL, sea level rise in CONUS is not expected to exceed 4 feet in 2100 and 7 feet in 2150, although it is not considered impossible. At higher GWLs, such extreme sea level rise becomes more likely within the next 100–150 years.

The total rise in sea level that will be realized beyond 2150 can differ by many feet depending on global warming levels over the next 50–100 years due to the potential for rapid and irreversible loss of ice from Greenland and Antarctica starting next century.[102,212,213] Such significant changes at 2100 and beyond translate directly into substantially increased frequency of flooding events in coastal regions, making major flooding events in some regions as common in 2100 as minor flooding events are currently.[67] However, there are also many processes that drive local variations in sea level rise that are not clearly related to global warming levels, such as vertical land motion. To aid in planning for uncertain future sea level rise, projections are also commonly used to construct sea level scenarios,[67] which are discussed in more detail in Chapter 9 and Appendix 3.

## Global Warming Changes the Oceans

Sea surface temperatures increase with the global warming level, but changes are not uniform across the globe: northern oceans are expected to warm faster than the tropics (Figure 2.13). Heat will continue to accumulate in the shallow and deep oceans: at a GWL of 4°C, ocean waters off the West Coast and Alaska could accumulate 3 billion joules per square meter, the Atlantic Coast 5 billion joules per square meter, and the Gulf of Mexico up to 6 billion joules per square meter—roughly the energy equivalent of two hundred pounds of TNT per square foot. As a result, the risk of marine heatwaves is projected to increase as the world warms. Projections indicate an increase of between 150 and 300 marine heatwave days per year if the GWL reaches 2.5°C. It is therefore possible that the coastal oceans of the United States could enter into near-permanent heatwave status, with significant ramifications for marine life.[214] The probability that September sea ice completely disappears from the Arctic Ocean, including Alaska coastal waters, rises from 1% in 2100 under a GWL of 1.5°C to 10%–30% at a GWL of 2°C.[79]

## Projected Changes to Sea Surface Temperatures at 1.5°C, 2°C, 3°C, and 4°C of Global Warming




**At higher global warming levels, sea surface temperatures are projected to change around the US coasts and open ocean, with implications for marine resources in those waters.**

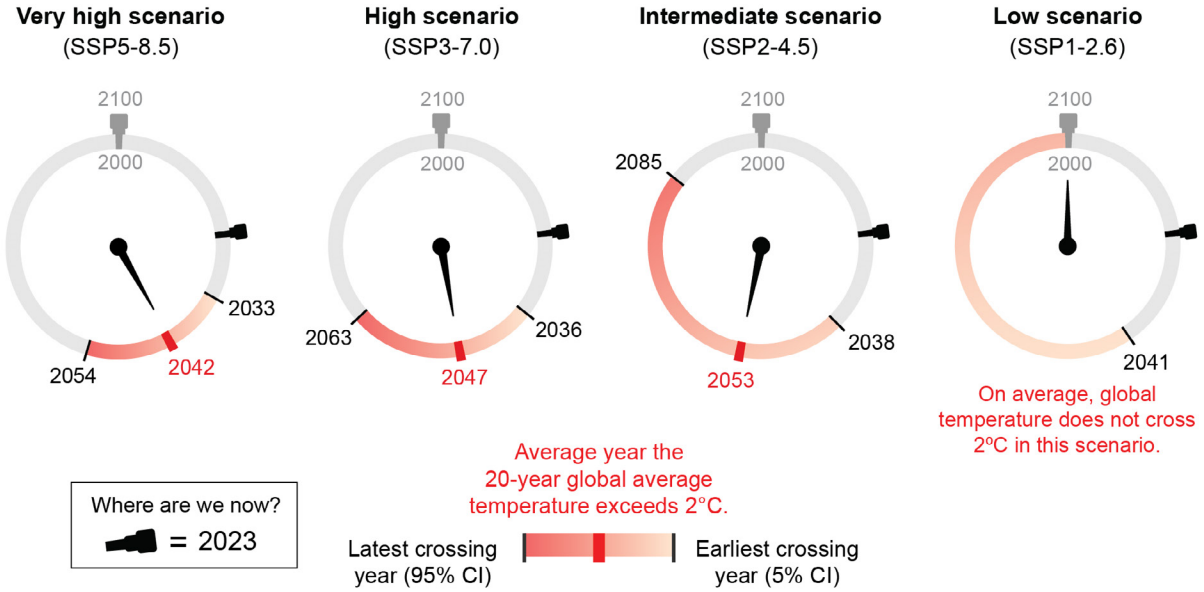
**Figure 2.13.** These maps show projected changes in sea surface temperatures (°F) for various global warming levels (1.5°, 2.0°, 3.0°, and 4.0°C). Changes are relative to the period 1851–1900. Figure credit: NOAA, NOAA NCEI, and CISESS NC.

Projected changes in ocean acidification and oxygen loss in US waters vary with location. For higher levels of future $CO_2$ emissions, the chemistry of waters in the Gulf of Maine will change in ways damaging to shell-building organisms, with the saturation level of aragonite—a form of calcium carbonate used by shell-building marine life—projected to fall below a crucial shell-building threshold for most of the year.[215] Ocean oxygen loss in the upper and middle depths will be most pronounced for the United States in the North Pacific, including off the coasts of Alaska and the Pacific Coast, which will squeeze the habitats of marine life moving away from warming waters at the surface.[216,217]

## *When or If We Reach a Particular Global Warming Threshold Depends on Future Emissions*

Projections of future global average surface temperature primarily depend on two things: 1) future emissions (Ch. 32) and 2) how sensitive the climate system is to these emissions (KM 3.2). In a very high scenario, the world is *very likely* to exceed a global warming level of 2°C between 2033 and 2054, depending on the climate sensitivity to greenhouse gas emissions (Ch. 3). In a low scenario, by contrast, the world is *very likely* not to cross this threshold at all (Figure 2.14). In addition to warming more, in high and very high scenarios, the Earth warms faster. The occurrence of some record-shattering extremes is dependent on this rate of warming.[218] Faster climate change also increases the challenge of adaptation for both human and natural systems.

## Projected Global Surface Temperature Change




**Future emissions of greenhouse gases determine whether and how quickly we reach 2°C of global warming.**

**Figure 2.14.** When (or if) the world reaches 2°C of global warming depends on future greenhouse gas emissions and the sensitivity of the climate system to those emissions. Shown are the IPCC AR6 assessed warming projections for four future scenarios, with projected years at which the 2°C (3.6°F) global warming level would be reached. For example, under a very high scenario (SSP5-8.5), models project reaching 2°C between 2033 and 2054, with an average estimate of 2042. Under a low scenario (SSP1-2.6), the 5% CI (confidence interval) range begins at 2041, but the average projection shows that warming would actually stay below 2°C. Figure credit: Project Drawdown, Stripe Inc., NOAA NCEI, and CISESS NC.

Over the past few years, a number of analyses have narrowed the plausible range of current emissions outcomes based on policies in place today (see existing US mitigation policies by state, Figure 32.20), putting the world on track for a central warming estimate of around 2.6°C (ranging from 2°–3.7°C) by 2100.[219,220,221,222,223,224] Existing climate pledges, if implemented, would increase the likelihood of limiting temperature change to well below 2°C.[225] To achieve more ambitious targets, stronger action would be needed. Emissions from existing and currently planned fossil fuel infrastructure globally would put the planet on a trajectory to exceed 1.5°C in the coming decades.[226] However, current policy projections represent neither a ceiling nor a floor on future climate outcomes. Our choices matter: global surface temperatures will continue to rise until $CO_2$ emissions reach net zero, and surface temperatures are not expected to fall for centuries in the absence of net-negative emissions. At the same time, Earth system models suggest that only a small amount of additional surface temperature change is expected over the next few centuries if $CO_2$ emissions reach net zero and there are deep reductions in other greenhouse gases, at least under scenarios where global warming is limited to 2°C or below by 2100.[227] In other words, additional warming over the next few centuries is not necessarily "locked in" after net $CO_2$ emissions fall to zero.

## *Some Impacts Are Inevitable Because of Past Choices*

While most models project that the Earth will stop warming if $CO_2$ emissions reach net zero, an end to warming does not imply an end to climate change. Because the $CO_2$ not removed by sinks on land and in the ocean remains in the atmosphere for thousands of years, the accumulation of past emissions already makes some impacts inevitable, regardless of future mitigation actions. Certain slow-moving aspects of the climate system such as ice sheets and the deep ocean take decades or centuries to respond to changes. This means that even in a low scenario where global warming slows or stops, some climate changes will continue as the Earth continues to adjust.

### Some Ocean Changes Are Locked In Even Under Aggressive Mitigation Scenarios

Past emissions will continue to affect the ocean for thousands of years. Regardless of future emissions, the surface ocean will continue to take up heat from the atmosphere, accumulating 2–4 times as much heat as has been taken up since 1970, even under low or very low scenarios.[79] This heat will have cascading effects on marine ecosystems, increasing the probability of marine heatwaves and causing sea level rise due to the expansion of warm water. Even after the world reaches net-zero emissions, oceans will continue to acidify as they gradually absorb the atmospheric $CO_2$ produced by past human activities.

### Sea Level Will Continue to Rise

Sea level along US coastlines is expected to continue rising regardless of global warming levels for the foreseeable future (at least for hundreds of years). Under a range of potential global warming levels, average sea level along US coastlines is *likely* to be between 12 and 20 inches above 2000 sea levels in 2050 (Figure 9.2).[67,88] At these short timescales, regional variations in projected sea level rise are large, with 4–12 inches of sea level rise *likely* in the Pacific Northwest and 20–27 inches of sea level rise *likely* in the western Gulf of Mexico. On timescales relevant to infrastructure planning (the design life of infrastructure ranges from 10 to more than 100 years), rates of sea level rise are also expected to continue accelerating under all but the lowest potential global warming levels (greater than 2°C).[67] Future projected changes in sea level will *likely* lead to an increased frequency of coastal flooding events in the continental United States over the next 30 years, with a greater-than-tenfold increase in typically damaging flooding events (e.g., storm surge currently recurring every few years) and a fivefold increase in destructive flooding events (e.g., major storm surge events currently recurring once in many decades) over this time period.[67] The onset of enhanced flooding frequency in coastal areas depends not only on the local trend in sea level but also low-frequency tidal cycles[228] and remote modes of natural climatic variability (e.g., ENSO, the Pacific Decadal Oscillation, and the North Atlantic Oscillation).[229]

### Adaptation to a Changing Climate Will Be Necessary

It is not possible to prevent climate change: the current global warming level is already over 1.1°C. The US, across all levels of government, business, and civil society, must both adapt to this reality of a changing climate and prepare for at least some level of additional warming. Inertia in the world's infrastructure[230] and economic and political systems[231] means that the near-term trend in risk over the next few decades is largely independent of the choice of emissions scenario,[224] and the climate benefits of aggressive action to reduce greenhouse gas emissions are unlikely to be realized in the near term. The faster and more extensive the warming, the greater the risk of climate impacts overtaking the speed of adaptation (KM 4.3), as there are both barriers and limits to adaptation (Ch. 31; KM 31.2). This means the US will need to adapt to a changing climate regardless of future emissions.

## *We Cannot Rule Out Catastrophic Outcomes*

### Climate Sensitivities Exceeding 4°C Are Unlikely but Not Impossible

There is no known precedent for a species changing its own climate as quickly as humans are changing ours, and there are many uncertainties associated with a rapidly warming world. Low-probability and potentially catastrophic outcomes are not impossible, and these risks persist even under current policies. While recent assessments (KM 3.2)[232] put the *likely* range of equilibrium climate sensitivity—the long-term warming the world will experience if atmospheric $CO_2$ concentrations are doubled—between 2.5°C and 4.0°C, higher values are not definitively ruled out, and feedback loops such as changes to cloud cover may lead to more warming in the future. Similarly, we cannot rule out a GWL of 4°C or more this century, particularly if climate change strongly reduces the ability of the biosphere or ocean to remove carbon from the atmosphere (Ch. 3).

### Changes to the Carbon Cycle May Increase the Amount of $CO_2$ Remaining in the Atmosphere

Our emerging understanding of land, ocean, coastal, and freshwater systems suggests the possibility of a decline in future carbon uptake capacity among both land and ocean ecosystems.[233,234,235] The balance of carbon uptake and release across terrestrial ecosystems depends on the relative balance of photosynthesis, respiration, and decomposition, which in turn strongly depends on temperature and moisture availability. Changes in either can alter the balance of carbon uptake and release across terrestrial ecosystems (Ch. 7). Similarly, the rate and extent to which atmospheric $CO_2$ is exchanged with ocean and freshwater systems is controlled by a combination of temperature, salinity, pressure, upwelling, and biological consumption and release of $CO_2$.

Although net land and ocean carbon sinks have increased in response to increased carbon emissions over the past six decades,[33,233] climate models project that the fraction of emissions taken up by land and oceans will decline, albeit with significant differences in regional responses and underlying mechanisms driving those responses.[1,236] For example, land reservoirs, such as tropical forests or the Arctic–boreal ecosystems, could switch from a net sink to a net source of carbon to the atmosphere (e.g., Huntzinger et al. 2018[234]).

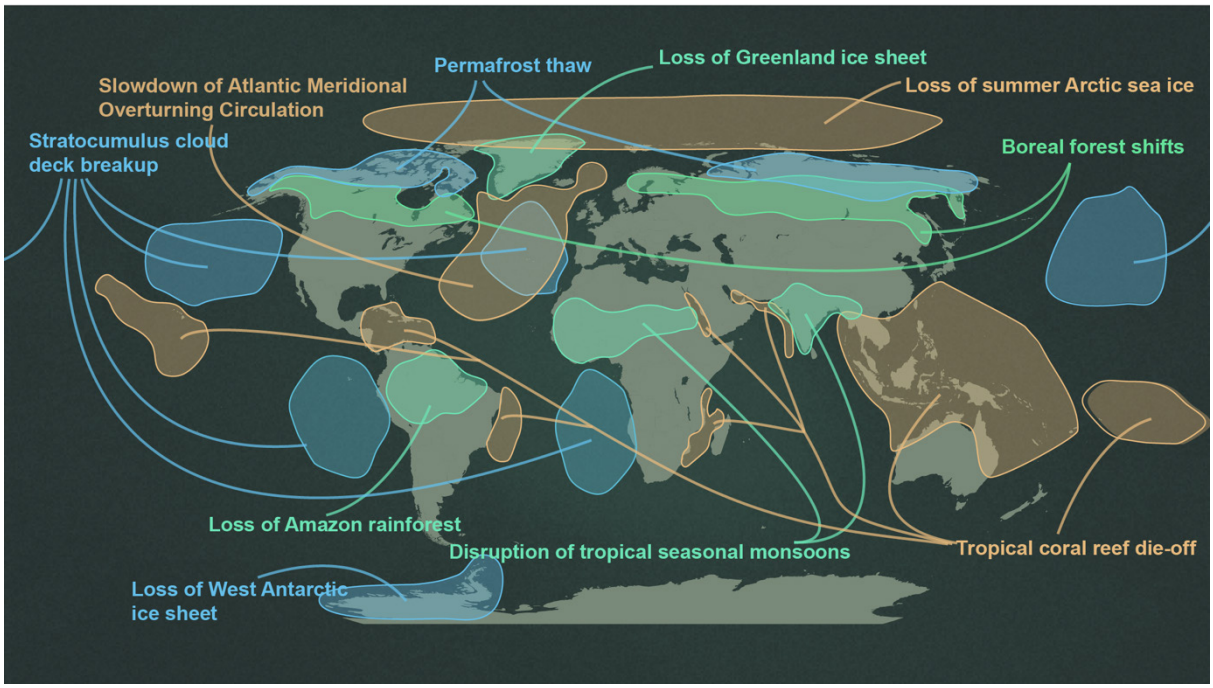
The Arctic–boreal region (Ch. 29) is particularly vulnerable to future climate change and rising temperatures, which could lead to the release of vast amounts of carbon from thawing permafrost, along with changes in vegetation productivity and disturbances such as wildfires and insect outbreaks. There is estimated to be about 4.8–5.9 trillion tons of carbon[237] frozen down to 20 meters in Arctic permafrost. This is roughly double the amount currently in the atmosphere and more than three times what already has been emitted to the atmosphere from fossil fuel use since preindustrial times. With rising temperatures and thawing soils, some of these carbon deposits may be mobilized to the atmosphere, primarily as $CO_2$. More than one hundred billion tons of $CO_2$ are *likely* to be released by thawing permafrost over the next century, with higher-end estimates of around 400 billion tons.[238] The total carbon emissions from thawing permafrost are expected to exceed the carbon captured by increases in vegetation productivity.[238] A smaller fraction of permafrost carbon will be emitted as the more powerful greenhouse gas methane. Methane emissions are projected to cause 40%–70% of total permafrost-affected radiative forcing in this century.[239]

### Tipping Elements Could Lead to Regional Rapid Changes

Tipping elements, or tipping points as they are colloquially known, are components of the Earth system that may respond to human-caused climate change by transitioning toward substantially different long-term states upon passing key thresholds.[240] In some cases, such changes could produce additional greenhouse gas emissions that could compound global warming.[241,242,243]

Systems that have been identified as possible tipping elements include the slowdown of the Atlantic Meridional Overturning Circulation, Arctic permafrost thaw, loss of the Greenland and West Antarctic ice sheets, Arctic sea ice loss, boreal forest shifts, disruption of tropical seasonal monsoons, Amazon rainforest dieback, tropical coral reef loss, and the disappearance of clouds that currently reflect sunlight cooling the Earth (Figure 2.15).[91] While some of these tipping elements are represented in modern Earth system models, many are still not, and the precise response of these systems to rapid climate change remains poorly understood. It is not possible to say that exceeding a particular GWL will trigger these tipping elements, nor are scientists certain that staying below a particular GWL will prevent them. However, the risk of these nonlinear changes increases with every increment of global warming.

## Possible Regional Tipping Elements




**Continued warming could push some aspects of the Earth system past tipping points.**

**Figure 2.15.** The figure shows 10 potential tipping elements in the climate system. These include changes to tropical and boreal forests and coral reefs, the loss of Greenland or West Antarctic ice sheets, and changes to the circulation of the oceans and the monsoons. The spatial area affected by each tipping element is shown; colors are used for visual clarity. Adapted with permission from Figure 1 in Wang et al. 2023,[240] which was adapted from McSweeney 2020.[244]

## Extreme Sea Level Rise Cannot Be Ruled Out

Increases in sea level along the continental US coast of 3–6 feet by 2100 and 5–12 feet by 2150, depending on human emissions, are distinct possibilities that cannot be ruled out (i.e., they have at least 1% chance of occurrence with global warming levels of 1.5°–4°C).[67,102,210] Beyond 2100, there is still substantial uncertainty in projected sea level rise under the most extreme scenarios of future warming and ice sheet mass loss.[210] This long-term uncertainty is primarily related to persistent gaps in our understanding of how glacier ice flows and fractures,[245,246,247] how snowfall changes under warming,[248] and how melt water behaves on the ice sheet surface.[249,250] Recent progress in better quantifying the uncertainties in the ice sheet contribution to future sea level projections[212,251] and ensuring that models accurately capture past ice sheet behavior[103,252] indicate that ice sheet models are quickly becoming better suited to produce usable and credible sea level projections. Continued model development can reduce uncertainty in the likelihood of extreme sea level rise

scenarios. In particular, there is strong incentive to continue reducing uncertainty surrounding the tail risks associated with potential low-likelihood but high-impact sea level rise projections past 2100, as planning for catastrophic outcomes makes adaptation much more costly.[253,254]

## The Biggest Uncertainty Is What We Will Do

Despite uncertainties in how land, ocean, atmosphere, and ice will respond to warming, and despite internal variability in the climate system, the largest source of uncertainty is the trajectory of our greenhouse gas emissions (KM 3.3). This is within human control and depends on our collective policy, economic, and social choices (Ch. 32). Although we probably will not be able to detect climate benefits from even the most aggressive possible emission reductions before the middle of the century, given the magnitude of internal climate variability, there are numerous co-benefits to mitigation in the near term, including improvements to air quality and health, reductions in mortality, and benefits to agriculture, the economy, and the labor market (KM 32.4).[14]

Human efforts to achieve rapid reductions in emissions can still limit global temperature changes to well below 2°C.[222] Global temperatures can be limited to 1.5°C above preindustrial levels by 2100 in scenarios where global $CO_2$ emissions reach net zero in the middle of this century alongside deep cuts to methane (KM 32.2) and other short-lived climate pollutants, with modest deployments of net-negative emissions thereafter.[255] Most of these scenarios have at least some midcentury temperature overshoot, however, which could result in irreversible consequences to global ecosystems (Ch. 8).[256] Still, the degree to which climate change will continue to worsen is in large part up to humans. The drastic emissions cuts required to stabilize global climate are possible (KM 32.1) and can be achieved in ways that are sustainable, healthy, and fair (KM 32.4). If emissions do not fall rapidly, the risks of extreme weather, compound events, and other climate impacts will continue to grow. How much more the world warms depends on the choices societies make today. The future is in human hands.

# Traceable Accounts

## *Acknowledgments*

The authors would like to thank Talia Resnick and Annika Larson for research assistance, including discussions about report structure, literature review, and bibliography management.

## *Process Description*

Most team members were selected from the pool of nominations received via the public call for authors; others were identified through extended networks to ensure diverse representation across multiple axes. The following areas of expertise were identified as crucial for Chapter 2:

- Paleoclimate and long-term context for climate trends
- Carbon cycle observations and greenhouse gases
- Infrastructure and resilience scenarios and projections in the CMIP6 (Coupled Model Intercomparison Project, Phase 6) models
- Regional trends
- Hurricanes, tropical cyclones, and midlatitude storms
- Ocean trends
- Cryosphere and sea level rise
- Climate extremes
- Diverse leadership in science
- Observations of climate trends

Author meetings were held virtually biweekly. Consensus was built by referring to the literature and leveraging the specific expertise of chapter authors. Engagement with other chapters occurred through formal presentations at the April 2022 chapter leadership meeting and one-on-one meetings between chapter lead authors.

## Key Message 2.1

## Climate Is Changing, and Scientists Understand Why

### Description of Evidence Base

The evidence base for human-caused increases in greenhouse gases (GHGs) is extensive and includes satellite and ground-based observations, solid theoretical understanding, and coherent measurements across multiple systems. Evidence for changes in aerosols includes long-term satellite and ground-based observations. Evidence for warming and other long-term climate changes has been extensively documented across multiple variables. Observations at smaller scales are noisier and regional signals more difficult to separate from natural internal climate variability.

Observational surface temperature records are available from a wide variety of scientific groups (e.g., Hansen et al. 2010;[2] Vose et al. 2021;[5] Morice et al. 2021;[3] Rohde and Hausfather 2020[4]). These temperature records combine land surface temperature data from weather stations with ocean sea surface temperature records from sources including ships and buoys. These records are corrected for inhomogeneities

introduced by changes in measurement techniques over time and use various different interpolation techniques to estimate temperature anomalies between measurement locations.

Long-term changes have been observed in many other aspects of the climate system. Seasonal average and extreme precipitation changes are widely documented using observations, and changes are consistent with our physical understanding. The evidence base for ocean changes includes long-term surface and subsurface ocean observations of temperature, salinity, oxygen, and pH in the coastal and open ocean and satellite data.

Paleoclimate evidence includes multiple proxy-based reconstructions and modeling.

Sea level rise over the industrial era has been measured with local tide gauges and satellite altimetry (since the 1970s). Changes in the processes contributing to sea level rise (ocean thermal expansion, glacier and ice sheet melt, and terrestrial freshwater discharges) have been independently measured using in situ techniques in the ocean (e.g., floats, ship-based measurements) and on ice sheets, as well as remotely (e.g., satellite gravimetry and interferometry). Changes in sea ice and lake ice over the past several decades at the poles have been extensively documented from satellites, including visible imagery, altimetry, and microwave backscatter.

Drought has many definitions including meteorological drought, agricultural drought, snow drought, and soil moisture drought; soil moisture projections depend on depth, with surface layers more responsive to short-term temperature changes, while deeper root-zone moisture changes on longer timescales. Moreover, drought can be defined on timescales ranging from several weeks to multidecadal megadroughts. The level of uncertainty in drought changes in several regions depends on the definitions and metrics used and the sources of measurements. Surface-based measurements of soil moisture are limited, and reliable satellite-based measurements of soil moisture are less than a decade long.

## Major Uncertainties and Research Gaps

### Uncertainty in Global Surface Temperature Reconstructions

In recent years, different groups producing global surface temperature records have somewhat converged in methodological approach, drawing on a larger set of collected weather station data[257,258] and using more granular interpolation approaches rather than simple latitude/longitude grid-cell averaging.[5] Published global surface temperature uncertainties on an annual basis range from ±0.13°C to ±0.2°C in the 1850s when records are more sparse to ±0.03°C to ±0.09°C at present across different surface temperature datasets, with differences between datasets driven by the number of measurements included, the spatial interpolation approach, and the method of uncertainty calculation.[4]

### Uncertainty in GHG Emissions Estimates from Inventories and Models

GHG emissions estimates are typically derived using either a "bottom-up" or a "top-down" approach.[259,260] The bottom-up approach uses a combination of activity data and emissions factors alongside empirical or process-based models to estimate the flux exchange between the different compartments of the land–ocean–atmosphere system. A primary advantage of the bottom-up approach is that it allows for explicit characterization of emissions and removals into specific sectors identified in the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories.[79,261] However, bottom-up emissions estimates can have significant uncertainty when the activity data or emissions factors are not well quantified or when process-based models are not well characterized due to missing processes or uncertain parameterization. On the other hand, the top-down approach aims to utilize the information from atmospheric greenhouse gas observations and atmospheric transport model to infer information about the distribution of emissions and removals at the surface of the Earth. For example, recent advancements in atmospheric $CO_2$ observations from satellites and top-down modeling approaches have allowed insights

into $CO_2$ emissions and removals at the national scale.[262] However, uncertainties in the modeling framework, spatial and temporal observational gaps, and uncertainties in the data may result in large uncertainties in the emissions estimates derived from the top-down approaches. Within the larger carbon cycle science community, various efforts are underway (e.g., REgional Carbon Cycle Assessment and Processes, Phase 2) to increase the level of agreement between estimates from these two approaches, thereby yielding more robust knowledge of GHG emissions.[263]

#### Uncertainty in Arctic Connections to Midlatitude Weather Extremes

Uncertainties in the influence of the Arctic on midlatitude weather extremes remain due to lack of consistency in model responses and observations, particularly for the winter season. Several advances in the physical understanding of how Arctic processes could influence midlatitude extremes in various seasons have been made since the publication of the Fourth National Climate Assessment,[264] yet the mechanisms continue to be a subject of debate in the scientific community.

#### Uncertainty in Drought Projections and Definitions

Drought projections are complicated by definitional ambiguity and the use of many standard metrics. For example, there is ambiguity in the definition of "flash drought," with more than 20 unique definitions present in the literature.[265] Moreover, agricultural drought depends not just on precipitation and temperature but also on evaporation and transpiration from the land surface—processes that are projected to change in a warmer world (Ch. 3). Metrics such as the standardized precipitation index or the Palmer Drought Severity Index that rely on meteorological values may yield different projections than indices that take into account land changes (such as precipitation minus evaporation).[266]

### Description of Confidence and Likelihood

It is unequivocal that global temperatures are increasing, and scientists are *virtually certain* that the planet has warmed between 1.1° and 1.2°C since the beginning of the industrial revolution, based on multiple observational datasets. There is *very high confidence* that this warming is driven by human-caused GHG emissions, which have increased by over 47% since 1850 based on modeling studies and theoretical understanding. There is *very high confidence* that changes outside the boundaries of the United States affect the Nation's climate because scientists understand the mechanisms by which melting in Antarctica and Greenland affect sea level in the US.[67] The links between tropical warming and atmospheric river intensity are due to well-understood atmospheric thermodynamics.[98,99] A wide range of detection and attribution studies (discussed in Ch. 3 and summarized in Eyring et al. 2021[267]) establish that long-term changes due to climate change have been observed in many aspects of the climate system.

## Key Message 2.2

# Extreme Events Are Becoming More Frequent and Severe

### Description of Evidence Base

Extreme events are rare by definition, but multiple datasets[125,268] indicate they are increasing. The authors have a solid theoretical understanding of how some events (heatwaves, downpours) should increase in a warming world (Ch. 3). Others (e.g., agricultural drought) depend on multiple interacting physical processes.[190,269] Event attribution now allows us to assign a quantifiable fraction of attributable risk to climate change (Ch. 3).

A wide variety of observational evidence exists for the occurrence of different storm types. Trained weather observers and storm spotters create storm reports across the country for severe hail, winds, and tornadoes. The National Weather Service (NWS) WSR-88D radar network maintains nationwide surveillance observations of precipitation, winds, and storm occurrence. The NWS additionally conducts storm damage surveys for high-impact events. NOAA and Air Force Hurricane Hunters conduct surveillance flights into tropical cyclones expected to impact US interests. NOAA geostationary satellite observations maintain a record of cloud properties and lightning occurrence. However, the length and representativeness of each data source are variable; storm reporting relates to population density and exposure, and the availability of trained observers impacts record quality, especially for transient phenomena such as hail.

### Major Uncertainties and Research Gaps

There is growing evidence that the impacts of climate change are, and will be, distributed unequally across US populations due to differences in both exposure and vulnerability. However, there are gaps in understanding the community-level impacts of projected changes in extreme events. Vulnerability at this level is in part a function of our investments (capital, operations, and management) in the built environment and natural resource functionality that serve to buffer these impacts (e.g., stormwater conveyance and levees to reduce flooding, water storage to relieve water shortages during drought). There is a lack of systematic assessment of these assets and other facets of vulnerability across the United States.

New literature has emerged documenting changes in certain types of compounding extremes such as heat and drought, but the limited observed record hinders quantifying long-term trends in several other compound extremes. Several frameworks for studying various compound extremes have emerged as well, and the physical understanding of certain compound extreme events such as heat/drought, heat/humidity, and coastal wind/precipitation/flooding has been documented, yet the understanding of the physical drivers of many other compound extremes is still emerging. Therefore, there are gaps in methodological advances, advances in understanding of their physical drivers, and studies quantifying projections in compound extreme risks.

The lack of homogenized daily and hourly temperature datasets limits our ability to reliably assess the evolution of extreme heat events over century-scale periods, although the availability of modern reanalysis products has increased agreement in changes in extreme heat events over the past 50 years.

There is limited research on changes in lightning activity due to lack of a long-term observational record. Satellite-based records and lightning detection networks are not sufficiently long to allow for detecting trends. Lightning can pose major hazards to society including direct casualties, igniting wildfires, and damaging energy infrastructure.[167]

### Description of Confidence and Likelihood

There is *very high confidence* that heatwaves globally are becoming more frequent and severe, based on multiple observational datasets. In the United States, there is *high confidence* that heatwaves in the West are becoming more common and severe based on observational records since 1901 (Figure 2.7). There is also *very high confidence* that climate change is and will continue to make rainfall extremes more intense. Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the authors also have *high confidence* that storms are delivering more rainfall and *high confidence* that storm surges are becoming higher. There is *very high confidence* that the Southwest is experiencing more severe drought: a recent paper found the 2002–2022 multidecadal soil moisture drought was the worst in the past 1,200 years.[135] The eastern region is experiencing reduced drought risk; studies suggest a transition toward more frequent extremes[141] and indicate that warming may partially counteract the effects of increased precipitation. Other extremes involve more complex interactions between human and natural systems: the occurrence and impacts of wildfires depend on fire ignition and suppression practices. However, while fire risk is not solely determined by climate factors, the authors have *very high confidence* that the hot and dry weather conditions that elevate fire risk are becoming more common.

## Key Message 2.3

## How Much the Climate Changes Depends on the Choices Made Now

### Description of Evidence Base

The Shared Socioeconomic Pathways (SSPs) were made available to the broader research community, replacing the old Representative Concentration Pathways (RCPs) and providing a more detailed assessment of the range of possible emissions pathways, as well as mitigation and adaptation challenges across different sets of socioeconomic assumptions.[270] A subset of the SSPs served as the basis for CMIP6 scenarios used in this Assessment and the Sixth Assessment Report (AR6) of the IPCC.[88]

CMIP6 provides a large set of model runs to use in evaluating different future emissions pathways and global warming levels. In addition, recent work assessing multiple lines of evidence from observational data, paleoclimate evidence, and physical process modeling has helped narrow the range of climate sensitivity.[232] The IPCC AR6 produced a new set of assessed warming projections based on these climate sensitivity estimates and CMIP6 models that were weighted based on their performance in reproducing historical temperatures.

The IPCC AR6 Working Group III[256] report explored a wider range of "overshoot" scenarios, where global temperatures temporarily exceed 1.5°C before being reduced through the large-scale use of negative-emissions technologies. Additionally, AR6 Working Group I provided a thorough exploration of the zero-emissions commitment associated with the cessation of carbon dioxide ($CO_2$) and other GHG emissions, building off the work of the Zero Emissions Commitment Model Intercomparison Project (ZECMIP).[227]

Recent literature summarized in IPCC AR6 Working Group III[256] and in Hausfather and Moore (2022)[219] provides a clearer sense of expected global average surface temperature outcomes under scenarios including only current policy, near-term 2030 commitments, and long-term net-zero commitments.

### Major Uncertainties and Research Gaps

Major uncertainties remain surrounding the emissions trajectories implied by current policies and the plausibility of worse-than-current-policy emissions outcomes. While most current policy scenarios in the literature project relatively flat global emissions over the next few decades, there are some (e.g., in the IPCC AR6 Working Group III scenario database) in which emissions continue to increase. Similarly, large uncer-

tainties remain when translating near-term and long-term mitigation commitments to global emissions pathways, particularly for non-$CO_2$ GHGs and other climate forcings like aerosols.

The translation from emissions scenarios to warming outcomes is complicated by uncertainties in both the sensitivity of the climate to emissions (both the transient climate response and the equilibrium climate sensitivity) and carbon cycle feedbacks that may affect the portion of emissions that accumulate in the atmosphere. Specifically for carbon cycle feedbacks, it will be the balance between the response of land and ocean systems to future climate that will determine the strength and extent of carbon uptake by these systems, whether they may become a net source of $CO_2$ to the atmosphere, and, consequently, the trajectory of future GHG forcings.

While recent work[232] has meaningfully narrowed the potential range of climate sensitivity, there are still tail risks of outcomes where equilibrium climate sensitivity exceeds 5°C or is below 2°C per doubling of atmospheric $CO_2$. There is also disagreement between a subset of high-sensitivity CMIP6 models and other lines of evidence supporting a narrower range of climate sensitivity.[271]

On timescales of less than 50 years, the most significant uncertainties in future sea level are due to regional and local variations in sea level rise and the interannual sea level variability intrinsic to the coastal ocean system. In Alaska and New England, the regional gravitational influence of glaciers and ice sheets may cause lower sea level rise or even sea level fall in the future, although the extent of these gravitational effects is highly dependent on the spatial fingerprint of glacier and ice sheet loss, which is uncertain.[100] Internal variability and human-caused changes in ocean circulation appear to have a strong effect on year-to-year sea level, particularly in the US Mid-Atlantic Coast,[272] but are not consistently simulated between models or included in the range of uncertainty in most sea level projections.[67]

On longer timescales (2100 and beyond), there are substantial uncertainties in projected sea level rise due to an incomplete understanding (and intermodel differences) of how the Greenland and Antarctic ice sheets will behave in a warmer climate. There is a consensus that past carbon emissions and even relatively moderate future global warming levels commit the planet to at least 3–6 feet of sea level rise over hundreds to thousands of years from the melting of the Greenland and Antarctic ice sheets.[273] However, there are many feet of uncertainty remaining both in the already-committed sea level rise and the sea level rise that could be expected under a range of global warming levels.[102,210,274,275] Ongoing research to understand how glaciers and ice sheets flow, fracture, and melt in response to climate change aims to narrow this wide range in sea level rise beyond 2100.

Projections of seasonal and extreme precipitation are widely studied and show more consistent and robust responses in extremes than average changes. The physical process link between higher temperatures and higher moisture availability in the atmosphere is well documented and understood. However, uncertainties remain in our understanding of the response of precipitation-producing systems, particularly those governed by mesoscale processes such as mesoscale convective systems and thunderstorms, which are not directly simulated in global climate models. Uncertainties, especially around how other factors that influence storm development (such as vertical wind shear and atmospheric instability) will change in future climates, link back to model uncertainty and bias at larger scales.

Uncertainty in drought projections arises from these uncertainties in precipitation. Climate models generally project drying in the US Southwest in response to elevated global warming levels, but the precipitation response is highly uncertain. The response of land vegetation also complicates drought projections. Under elevated $CO_2$ levels, certain types of plants may become more efficient at using water due to a physiological response. This is expected to be at least partially counteracted by greening in response to elevated $CO_2$ levels. Additionally, the vegetation response to increased heat stress, extreme precipitation, and fire risk is complex and not yet fully understood.

## Description of Confidence and Likelihood

There is *very high confidence* that many impacts—both changes to the average state and the risk of extreme events—will intensify as the temperature increases. This is based on physical understanding of the underlying drivers reflected in climate models of varying complexity, including the state-of-the-art general circulation models participating in CMIP6.[276] It is an unequivocal fact, backed by over 100 years of theory and observation, that warming increases with GHG emissions,[277] and warming is *virtually certain* to continue at current levels of emissions. There is *very high confidence* that warming will continue at least until emissions of carbon dioxide reach net zero. The cessation of warming at the point of (net) zero $CO_2$ emissions (called the zero-emissions commitment, or ZEC) traces back to Matthews and Caldeira (2008),[278] Solomon et al. (2009),[279] and Matthews and Weaver (2010),[280] who were among the first to explore zero-emissions scenarios in emissions-driven climate model runs. The common conflation of constant concentration scenarios with zero-emissions scenarios has led to the misconception that substantial future warming is inevitable. In the lead-up to AR6, there was a desire by the community to further explore the robustness of ZEC results. This led to the creation of ZECMIP, where 18 different Earth system models were used to examine ZEC under a variety of emissions-reduction pathways and cumulative emissions scenarios. ZECMIP broadly found that ZEC was 0°C ± 0.3°C across the Earth system models examined.[227] Hence, rapidly reducing emissions would *very likely* limit future warming (*very high confidence*). It is *very likely* that the eventual global warming in response to a doubling of atmospheric $CO_2$ is between 2.3° and 4.7°C and *likely* that the warming would be between 2.6° and 3.9°C.[232] There is *high confidence* that catastrophic scenarios where warming exceeds 4°C cannot be ruled out due to uncertainties in climate sensitivity, carbon cycle feedbacks,[239,281] and emissions scenarios.[282]

# References


1. Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Ch. 5. Global carbon and other biogeochemical cycles and feedbacks. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 673–816. https://doi.org/10.1017/9781009157896.007

2. Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Reviews of Geophysics*, **48** (4), 4004. https://doi.org/10.1029/2010rg000345

3. Morice, C.P., J.J. Kennedy, N.A. Rayner, J.P. Winn, E. Hogan, R.E. Killick, R.J.H. Dunn, T.J. Osborn, P.D. Jones, and I.R. Simpson, 2021: An updated assessment of near-surface temperature change from 1850: The HadCRUT5 data set. *Journal of Geophysical Research: Atmospheres*, **126** (3), e2019JD032361. https://doi.org/10.1029/2019jd032361

4. Rohde, R.A. and Z. Hausfather, 2020: The Berkeley Earth land/ocean temperature record. *Earth System Science Data*, **12** (4), 3469–3479. https://doi.org/10.5194/essd-12-3469-2020

5. Vose, R.S., B. Huang, X. Yin, D. Arndt, D.R. Easterling, J.H. Lawrimore, M.J. Menne, A. Sanchez-Lugo, and H.M. Zhang, 2021: Implementing full spatial coverage in NOAA's global temperature analysis. *Geophysical Research Letters*, **48** (4), e2020GL090873. https://doi.org/10.1029/2020gl090873

6. Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A.D. Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, 2021: Ch. 11. Weather and climate extreme events in a changing climate. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1513–1766. https://doi.org/10.1017/9781009157896.013

7. Herring, S.C., N. Christidis, A. Hoell, and P.A. Stott, 2022: Explaining extreme events of 2020 from a climate perspective. *Bulletin of the American Meteorological Society*, **103** (3), S1–S117. https://doi.org/10.1175/bams-explainingextremeevents2020.1

8. Philip, S.Y., S.F. Kew, G.J. van Oldenborgh, F.S. Anslow, S.I. Seneviratne, R. Vautard, D. Coumou, K.L. Ebi, J. Arrighi, R. Singh, M. van Aalst, C. Pereira Marghidan, M. Wehner, W. Yang, S. Li, D.L. Schumacher, M. Hauser, R. Bonnet, L.N. Luu, F. Lehner, N. Gillett, J. Tradowsky, G.A. Vecchi, C. Rodell, R.B. Stull, R. Howard, and F.E.L. Otto, 2021: Rapid attribution analysis of the extraordinary heat wave on the Pacific coast of the US and Canada in June 2021. *Earth System Dynamics*, **13** (4), 1689–1713. https://doi.org/10.5194/esd-13-1689-2022

9. Risser, M.D. and M.F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophysical Research Letters*, **44** (24), 12457–12464. https://doi.org/10.1002/2017gl075888

10. van Oldenborgh, G.J., K. van der Wiel, A. Sebastian, R. Singh, J. Arrighi, F. Otto, K. Haustein, S. Li, G. Vecchi, and H. Cullen, 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12** (12), 124009. https://doi.org/10.1088/1748-9326/aa9ef2

11. Wang, S.Y.S., L. Zhao, J.-H. Yoon, P. Klotzbach, and R.R. Gillies, 2018: Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas. *Environmental Research Letters*, **13** (5), 054014. https://doi.org/10.1088/1748-9326/aabb85

12. Vaidyanathan, A., J. Malilay, P. Schramm, and S. Saha, 2020: Heat-related deaths—United States, 2004–2018. *Morbidity and Mortality Weekly Report*, **69** (24), 729–734. https://doi.org/10.15585/mmwr.mm6924a1

13. Sarofim, M.C., S. Saha, M.D. Hawkins, D.M. Mills, J. Hess, R. Horton, P. Kinney, J. Schwartz, and A. St. Juliana, 2016: Ch. 2. Temperature-related death and illness. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 43–68. https://doi.org/10.7930/j0mg7mdx

14. Shindell, D., Y. Zhang, M. Scott, M. Ru, K. Stark, and K.L. Ebi, 2020: The effects of heat exposure on human mortality throughout the United States. *GeoHealth*, **4** (4), e2019GH000234. https://doi.org/10.1029/2019gh000234

15. NCEI, 2022: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

16. Iglesias, V., A.E. Braswell, M.W. Rossi, M.B. Joseph, C. McShane, M. Cattau, M.J. Koontz, J. McGlinchy, R.C. Nagy, J. Balch, S. Leyk, and W.R. Travis, 2021: Risky development: Increasing exposure to natural hazards in the United States. *Earth's Future*, **9** (7), e2020EF001795. https://doi.org/10.1029/2020ef001795

17. EPA, 2022: Climate Change Indicators: Heat-Related Deaths. U.S. Environmental Protection Agency. https://www.epa.gov/climate-indicators/climate-change-indicators-heat-related-deaths

18. Wehner, M. and C. Sampson, 2021: Attributable human-induced changes in the magnitude of flooding in the Houston, Texas region during Hurricane Harvey. *Climatic Change*, **166** (1), 1–13. https://doi.org/10.1007/s10584-021-03114-z

19. Smiley, K.T., I. Noy, M.F. Wehner, D. Frame, C.C. Sampson, and O.E.J. Wing, 2022: Social inequalities in climate change-attributed impacts of Hurricane Harvey. *Nature Communications*, **13** (1), 3418. https://doi.org/10.1038/s41467-022-31056-2

20. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. https://doi.org/10.3390/cli8010012

21. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

22. Raymond, W.W., J.S. Barber, M.N. Dethier, H.A. Hayford, C.D.G. Harley, T.L. King, B. Paul, C.A. Speck, E.D. Tobin, A.E.T. Raymond, and P.S. McDonald, 2022: Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. *Ecology*, **103** (10), e3798. https://doi.org/10.1002/ecy.3798

23. Kalashnikov, D.A., J.L. Schnell, J.T. Abatzoglou, D.L. Swain, and D. Singh, 2022: Increasing co-occurrence of fine particulate matter and ground-level ozone extremes in the western United States. *Science Advances*, **8** (1), 9386. https://doi.org/10.1126/sciadv.abi9386

24. Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, J.T. Abatzoglou, K. Bolles, S.H. Baek, A.M. Badger, and B. Livneh, 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368** (6488), 314–318. https://doi.org/10.1126/science.aaz9600

25. Kunkel, K.E., T.R. Karl, M.F. Squires, X. Yin, S.T. Stegall, and D.R. Easterling, 2020: Precipitation extremes: Trends and relationships with average precipitation and precipitable water in the contiguous United States. *Journal of Applied Meteorology and Climatology*, **59** (1), 125–142. https://doi.org/10.1175/jamc-d-19-0185.1

26. IPCC, 2021: Summary for policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–32. https://doi.org/10.1017/9781009157896.001

27. Etheridge, D.M., L.P. Steele, R.L. Langenfelds, R.J. Francey, J.-M. Barnola, and V.I. Morgan, 1996: Natural and anthropogenic changes in atmospheric $CO_2$ over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research: Atmospheres*, **101** (D2), 4115–4128. https://doi.org/10.1029/95jd03410

28. Lan, X., P. Tans, and K.W. Thoning, 2023: Trends in Globally-Averaged $CO_2$ Determined from NOAA Global Monitoring Laboratory Measurements. Version 2023-03. National Oceanic and Atmospheric Administration, Global Monitoring Laboratory. https://www.gml.noaa.gov/ccgg/trends/

29. Kirschke, S., P. Bousquet, P. Ciais, M. Saunois, J.G. Canadell, E.J. Dlugokencky, P. Bergamaschi, D. Bergmann, D.R. Blake, L. Bruhwiler, P. Cameron-Smith, S. Castaldi, F. Chevallier, L. Feng, A. Fraser, M. Heimann, E.L. Hodson, S. Houweling, B. Josse, P.J. Fraser, P.B. Krummel, J.-F. Lamarque, R.L. Langenfelds, C. Le Quéré, V. Naik, S. O'Doherty, P.I. Palmer, I. Pison, D. Plummer, B. Poulter, R.G. Prinn, M. Rigby, B. Ringeval, M. Santini, M. Schmidt, D.T. Shindell, I.J. Simpson, R. Spahni, L.P. Steele, S.A. Strode, K. Sudo, S. Szopa, G.R. van der Werf, A. Voulgarakis, M. van Weele, R.F. Weiss, J.E. Williams, and G. Zeng, 2013: Three decades of global methane sources and sinks. *Nature Geoscience*, **6** (10), 813–823. https://doi.org/10.1038/ngeo1955

30. Saunois, M., A.R. Stavert, B. Poulter, P. Bousquet, J.G. Canadell, R.B. Jackson, P.A. Raymond, E.J. Dlugokencky, S. Houweling, P.K. Patra, P. Ciais, V.K. Arora, D. Bastviken, P. Bergamaschi, D.R. Blake, G. Brailsford, L. Bruhwiler, K.M. Carlson, M. Carrol, S. Castaldi, N. Chandra, C. Crevoisier, P.M. Crill, K. Covey, C.L. Curry, G. Etiope, C. Frankenberg, N. Gedney, M.I. Hegglin, L. Höglund-Isaksson, G. Hugelius, M. Ishizawa, A. Ito, G. Janssens-Maenhout, K.M. Jensen, F. Joos, T. Kleinen, P.B. Krummel, R.L. Langenfelds, G.G. Laruelle, L. Liu, T. Machida, S. Maksyutov, K.C. McDonald, J. McNorton, P.A. Miller, J.R. Melton, I. Morino, J. Müller, F. Murguia-Flores, V. Naik, Y. Niwa, S. Noce, S. O'Doherty, R.J. Parker, C. Peng, S. Peng, G.P. Peters, C. Prigent, R. Prinn, M. Ramonet, P. Regnier, W.J. Riley, J.A. Rosentreter, A. Segers, I.J. Simpson, H. Shi, S.J. Smith, L.P. Steele, B.F. Thornton, H. Tian, Y. Tohjima, F.N. Tubiello, A. Tsuruta, N. Viovy, A. Voulgarakis, T.S. Weber, M. van Weele, G.R. van der Werf, R.F. Weiss, D. Worthy, D. Wunch, Y. Yin, Y. Yoshida, W. Zhang, Z. Zhang, Y. Zhao, B. Zheng, Q. Zhu, Q. Zhu, and Q. Zhuang, 2020: The global methane budget 2000–2017. *Earth System Science Data*, **12** (3), 1561–1623. https://doi.org/10.5194/essd-12-1561-2020

31. Lan, X., K.W. Thoning, and E.J. Dlugokencky, 2022: Trends in Globally-Averaged $CH_4$, $N_2O$, and $SF_6$ Determined from NOAA Global Monitoring Laboratory Measurements. Version 2023-04. National Oceanic and Atmospheric Administration, Global Monitoring Laboratory. https://doi.org/10.15138/p8xg-aa10

32. Prather, M.J., J. Hsu, N.M. DeLuca, C.H. Jackman, L.D. Oman, A.R. Douglass, E.L. Fleming, S.E. Strahan, S.D. Steenrod, O.A. Søvde, I.S.A. Isaksen, L. Froidevaux, and B. Funke, 2015: Measuring and modeling the lifetime of nitrous oxide including its variability. *Journal of Geophysical Research: Atmospheres*, **120** (11), 5693–5705. https://doi.org/10.1002/2015jd023267

33. Friedlingstein, P., M. O'Sullivan, M.W. Jones, R.M. Andrew, L. Gregor, et al., 2022: Global carbon budget 2022. *Earth System Science Data*, **14** (11), 4811–4900. https://doi.org/10.5194/essd-14-4811-2022

34. Le Quéré, C., R.B. Jackson, M.W. Jones, A.J.P. Smith, S. Abernethy, R.M. Andrew, A.J. De-Gol, D.R. Willis, Y. Shan, J.G. Canadell, P. Friedlingstein, F. Creutzig, and G.P. Peters, 2020: Temporary reduction in daily global $CO_2$ emissions during the COVID-19 forced confinement. *Nature Climate Change*, **10** (7), 647–653. https://doi.org/10.1038/s41558-020-0797-x

35. Liu, Z., P. Ciais, Z. Deng, R. Lei, S.J. Davis, S. Feng, B. Zheng, D. Cui, X. Dou, B. Zhu, R. Guo, P. Ke, T. Sun, C. Lu, P. He, Y. Wang, X. Yue, Y. Wang, Y. Lei, H. Zhou, Z. Cai, Y. Wu, R. Guo, T. Han, J. Xue, O. Boucher, E. Boucher, F. Chevallier, K. Tanaka, Y. Wei, H. Zhong, C. Kang, N. Zhang, B. Chen, F. Xi, M. Liu, F.-M. Bréon, Y. Lu, Q. Zhang, D. Guan, P. Gong, D.M. Kammen, K. He, and H.J. Schellnhuber, 2020: Near-real-time monitoring of global $CO_2$ emissions reveals the effects of the COVID-19 pandemic. *Nature Communications*, **11** (1), 5172. https://doi.org/10.1038/s41467-020-18922-7

36. Laughner, J.L., J.L. Neu, D. Schimel, P.O. Wennberg, K. Barsanti, K.W. Bowman, A. Chatterjee, B.E. Croes, H.L. Fitzmaurice, D.K. Henze, J. Kim, E.A. Kort, Z. Liu, K. Miyazaki, A.J. Turner, S. Anenberg, J. Avise, H. Cao, D. Crisp, J.d. Gouw, A. Eldering, J.C. Fyfe, D.L. Goldberg, K.R. Gurney, S. Hasheminassab, F. Hopkins, C.E. Ivey, D.B.A. Jones, J. Liu, N.S. Lovenduski, R.V. Martin, G.A. McKinley, L. Ott, B. Poulter, M. Ru, S.P. Sander, N. Swart, Y.L. Yung, and Z.-C. Zeng, 2021: Societal shifts due to COVID-19 reveal large-scale complexities and feedbacks between atmospheric chemistry and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (46), e2109481118. https://doi.org/10.1073/pnas.2109481118

37. Lovenduski, N.S., A. Chatterjee, N.C. Swart, J.C. Fyfe, R.F. Keeling, and D. Schimel, 2021: On the detection of COVID-driven changes in atmospheric carbon dioxide. *Geophysical Research Letters*, **48** (22), e2021GL095396. https://doi.org/10.1029/2021gl095396

38. Jones, M.W., G.P. Peters, T. Gasser, R.M. Andrew, C. Schwingshackl, J. Gütschow, R.A. Houghton, P. Friedlingstein, J. Pongratz, and C. Le Quéré, 2023: National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *Scientific Data*, **10** (1), 155. https://doi.org/10.1038/s41597-023-02041-1

39. Thakrar, S.K., S. Balasubramanian, P.J. Adams, I.M.L. Azevedo, N.Z. Muller, S.N. Pandis, S. Polasky, C.A. Pope, A.L. Robinson, J.S. Apte, C.W. Tessum, J.D. Marshall, and J.D. Hill, 2020: Reducing mortality from air pollution in the United States by targeting specific emission sources. *Environmental Science & Technology Letters*, **7** (9), 639–645. https://doi.org/10.1021/acs.estlett.0c00424

40. Gettelman, A., R. Lamboll, C.G. Bardeen, P.M. Forster, and D. Watson-Parris, 2021: Climate impacts of COVID-19 induced emission changes. *Geophysical Research Letters*, **48** (3), e2020GL091805. https://doi.org/10.1029/2020gl091805

41. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.001

42. Szopa, S., V. Naik, B. Adhikary, P. Artaxo, T. Berntsen, W.D. Collins, S. Fuzzi, L. Gallardo, A. Kiendler-Scharr, Z. Klimont, H. Liao, N. Unger, and P. Zanis, 2021: Ch. 6. Short-lived climate forcers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 817–922. https://doi.org/10.1017/9781009157896.008

43. Dangendorf, S., M. Marcos, G. Wöppelmann, C.P. Conrad, T. Frederikse, and R. Riva, 2017: Reassessment of 20th century global mean sea level rise. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (23), 5946–5951. https://doi.org/10.1073/pnas.1616007114

44. Frederikse, T., F. Landerer, L. Caron, S. Adhikari, D. Parkes, V.W. Humphrey, S. Dangendorf, P. Hogarth, L. Zanna, L. Cheng, and Y.-H. Wu, 2020: The causes of sea-level rise since 1900. *Nature*, **584** (7821), 393–397. https://doi.org/10.1038/s41586-020-2591-3

45. Nerem, R.S., B.D. Beckley, J.T. Fasullo, B.D. Hamlington, D. Masters, and G.T. Mitchum, 2018: Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (9), 2022–2025. https://doi.org/10.1073/pnas.1717312115

46. Bartoli, G., B. Hönisch, and R.E. Zeebe, 2011: Atmospheric $CO_2$ decline during the Pliocene intensification of Northern Hemisphere glaciations. *Paleoceanography*, **26** (4). https://doi.org/10.1029/2010pa002055

47. Martínez-Botí, M.A., G.L. Foster, T.B. Chalk, E.J. Rohling, P.F. Sexton, D.J. Lunt, R.D. Pancost, M.P.S. Badger, and D.N. Schmidt, 2015: Plio-Pleistocene climate sensitivity evaluated using high-resolution $CO_2$ records. *Nature*, **518** (7537), 49–54. https://doi.org/10.1038/nature14145

48. Dumitru, O.A., J. Austermann, V.J. Polyak, J.J. Fornós, Y. Asmerom, J. Ginés, A. Ginés, and B.P. Onac, 2019: Constraints on global mean sea level during Pliocene warmth. *Nature*, **574** (7777), 233–236. https://doi.org/10.1038/s41586-019-1543-2

49. Gulev, S.K., P.W. Thorne, J. Ahn, F.J. Dentener, C.M. Domingues, S. Gerland, D. Gong, D.S. Kaufman, H.C. Nnamchi, J. Quaas, J.A. Rivera, S. Sathyendranath, S.L. Smith, B. Trewin, K. von Schuckmann, and R.S. Vose, 2021: Ch. 2. Changing state of the climate system. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 287–422. https://doi.org/10.1017/9781009157896.004

50. Rantanen, M., A.Y. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma, and A. Laaksonen, 2022: The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, **3** (1), 168. https://doi.org/10.1038/s43247-022-00498-3

51. Banerjee, A., L.M. Polvani, and J.C. Fyfe, 2017: The United States "warming hole": Quantifying the forced aerosol response given large internal variability. *Geophysical Research Letters*, **44** (4), 1928–1937. https://doi.org/10.1002/2016gl071567

52. Kumar, S., J. Kinter, P.A. Dirmeyer, Z. Pan, and J. Adams, 2013: Multidecadal climate variability and the "warming hole" in North America: Results from CMIP5 twentieth- and twenty-first-century climate simulations. *Journal of Climate*, **26** (11), 3511–3527. https://doi.org/10.1175/jcli-d-12-00535.1

53. Mascioli, N.R., M. Previdi, A.M. Fiore, and M. Ting, 2017: Timing and seasonality of the United States 'warming hole'. *Environmental Research Letters*, **12** (3), 034008. https://doi.org/10.1088/1748-9326/aa5ef4

54. Partridge, T.F., J.M. Winter, E.C. Osterberg, D.W. Hyndman, A.D. Kendall, and F.J. Magilligan, 2018: Spatially distinct seasonal patterns and forcings of the U.S. warming hole. *Geophysical Research Letters*, **45** (4), 2055–2063. https://doi.org/10.1002/2017gl076463

55. Weaver, S.J., 2013: Factors associated with decadal variability in Great Plains summertime surface temperatures. *Journal of Climate*, **26** (1), 343–350. https://doi.org/10.1175/jcli-d-11-00713.1

56. Alter, R.E., H.C. Douglas, J.M. Winter, and E.A.B. Eltahir, 2018: Twentieth century regional climate change during the summer in the central United States attributed to agricultural intensification. *Geophysical Research Letters*, **45** (3), 1586–1594. https://doi.org/10.1002/2017gl075604

57. Mueller, N.D., E.E. Butler, K.A. McKinnon, A. Rhines, M. Tingley, N.M. Holbrook, and P. Huybers, 2016: Cooling of US Midwest summer temperature extremes from cropland intensification. *Nature Climate Change*, **6** (3), 317–322. https://doi.org/10.1038/nclimate2825

58. Leibensperger, E.M., L.J. Mickley, D.J. Jacob, W.T. Chen, J.H. Seinfeld, A. Nenes, P.J. Adams, D.G. Streets, N. Kumar, and D. Rind, 2012: Climatic effects of 1950–2050 changes in US anthropogenic aerosols—Part 2: Climate response. *Atmospheric Chemistry and Physics*, **12** (7), 3349–3362. https://doi.org/10.5194/acp-12-3349-2012

59. Ghate, V.P., A.G. Carlton, T. Surleta, and A.M. Burns, 2022: Changes in aerosols, meteorology, and radiation in the southeastern U.S. warming hole region during 2000 to 2019. *Journal of Climate*, **35** (23), 4125–4137. https://doi.org/10.1175/jcli-d-22-0073.1

60. Knutson, T.R. and F. Zeng, 2018: Model assessment of observed precipitation trends over land regions: Detectable human influences and possible low bias in model trends. *Journal of Climate*, **31** (12), 4617–4637. https://doi.org/10.1175/jcli-d-17-0672.1

61. Bishop, D.A., A.P. Williams, R. Seager, A.M. Fiore, B.I. Cook, J.S. Mankin, D. Singh, J.E. Smerdon, and M.P. Rao, 2019: Investigating the causes of increased twentieth-century fall precipitation over the southeastern United States. *Journal of Climate*, **32** (2), 575–590. https://doi.org/10.1175/jcli-d-18-0244.1

62. Goss, M., D.L. Swain, J.T. Abatzoglou, A. Sarhadi, C.A. Kolden, A.P. Williams, and N.S. Diffenbaugh, 2020: Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters*, **15** (9), 094016. https://doi.org/10.1088/1748-9326/ab83a7

63. Zhang, F., J.A. Biederman, M.P. Dannenberg, D. Yan, S.C. Reed, and W.K. Smith, 2021: Five decades of observed daily precipitation reveal longer and more variable drought events across much of the western United States. *Geophysical Research Letters*, **48** (7), e2020GL092293. https://doi.org/10.1029/2020gl092293

64. Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams, Jr., C. Fenimore, K. Gleason, and D. Arndt, 2014: Improved historical temperature and precipitation time series for U.S. climate divisions. *Journal of Applied Meteorology and Climatology*, **53** (5), 1232–1251. https://doi.org/10.1175/jamc-d-13-0248.1

65. Vose, R.S., M. Squires, D. Arndt, I. Durre, C. Fenimore, K. Gleason, M.J. Menne, J. Partain, C.N. Williams Jr., P.A. Bieniek, and R.L. Thoman, 2017: Deriving historical temperature and precipitation time series for Alaska climate divisions via climatologically aided interpolation. *Journal of Service Climatology*, **10** (1), 20. https://doi.org/10.46275/joasc.2017.10.001

66. Becker, A., P. Finger, A. Meyer-Christoffer, B. Rudolf, K. Schamm, U. Schneider, and M. Ziese, 2013: A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present. *Earth System Science Data*, **5** (1), 71–99. https://doi.org/10.5194/essd-5-71-2013

67. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

68. Dangendorf, S., C. Hay, F.M. Calafat, M. Marcos, C.G. Piecuch, K. Berk, and J. Jensen, 2019: Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change*, **9** (9), 705–710. https://doi.org/10.1038/s41558-019-0531-8

69. Harvey, T.C., B.D. Hamlington, T. Frederikse, R.S. Nerem, C.G. Piecuch, W.C. Hammond, G. Blewitt, P.R. Thompson, D.P.S. Bekaert, F.W. Landerer, J.T. Reager, R.E. Kopp, H. Chandanpurkar, I. Fenty, D. Trossman, J.S. Walker, and C. Boening, 2021: Ocean mass, sterodynamic effects, and vertical land motion largely explain US coast relative sea level rise. *Communications Earth & Environment*, **2** (1), 233. https://doi.org/10.1038/s43247-021-00300-w

70. Little, C.M., A. Hu, C.W. Hughes, G.D. McCarthy, C.G. Piecuch, R.M. Ponte, and M.D. Thomas, 2019: The relationship between U.S. East Coast sea level and the Atlantic Meridional Overturning Circulation: A review. *Journal of Geophysical Research: Oceans*, **124** (9), 6435–6458. https://doi.org/10.1029/2019jc015152

71. Bromirski, P.D., A.J. Miller, R.E. Flick, and G. Auad, 2011: Dynamical suppression of sea level rise along the Pacific coast of North America: Indications for imminent acceleration. *Journal of Geophysical Research*, **116** (C7), C07005. https://doi.org/10.1029/2010jc006759

72. Sweet, W., G. Dusek, J.T.B. Obeysekera, and J.J. Marra, 2018: Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold. NOAA Technical Report NOS CO-OPS 086. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD. https://doi.org/10.7289/v5/tr-nos-coops-086

73. Wdowinski, S., R. Bray, B.P. Kirtman, and Z. Wu, 2016: Increasing flooding hazard in coastal communities due to rising sea level: Case study of Miami Beach, Florida. *Ocean & Coastal Management*, **126**, 1–8. https://doi.org/10.1016/j.ocecoaman.2016.03.002

74. Pershing, A.J., M.A. Alexander, C.M. Hernandez, L.A. Kerr, A. Le Bris, K.E. Mills, J.A. Nye, N.R. Record, H.A. Scannell, J.D. Scott, G.D. Sherwood, and A.C. Thomas, 2015: Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science*, **350** (6262), 809–812. https://doi.org/10.1126/science.aac9819

75. Smale, D.A., T. Wernberg, E.C.J. Oliver, M. Thomsen, B.P. Harvey, S.C. Straub, M.T. Burrows, L.V. Alexander, J.A. Benthuysen, M.G. Donat, M. Feng, A.J. Hobday, N.J. Holbrook, S.E. Perkins-Kirkpatrick, H.A. Scannell, A. Sen Gupta, B.L. Payne, and P.J. Moore, 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9** (4), 306–312. https://doi.org/10.1038/s41558-019-0412-1

76. Jewett, L. and A. Romanou, 2017: Ch. 13. Ocean acidification and other ocean changes. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 364–392. https://doi.org/10.7930/j0qv3jqb

77. Breitburg, D., L.A. Levin, A. Oschlies, M. Grégoire, F.P. Chavez, D.J. Conley, V. Garçon, D. Gilbert, D. Gutiérrez, K. Isensee, G.S. Jacinto, K.E. Limburg, I. Montes, S.W.A. Naqvi, G.C. Pitcher, N.N. Rabalais, M.R. Roman, K.A. Rose, B.A. Seibel, M. Telszewski, M. Yasuhara, and J. Zhang, 2018: Declining oxygen in the global ocean and coastal waters. *Science*, **359** (6371), 7240. https://doi.org/10.1126/science.aam7240

78. Hicke, J.A., S. Lucatello, L.D. Mortsch, J. Dawson, M.D. Aguilar, C.A.F. Enquist, E.A. Gilmore, D.S. Gutzler, S. Harper, K. Holsman, E.B. Jewett, T.A. Kohler, and K. Miller, 2022: Ch. 14. North America. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1929–2042. https://doi.org/10.1017/9781009325844.016

79. IPCC, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964

80. Committee on Environment and Natural Resources, 2010: Scientific Assessment of Hypoxia in U.S. Coastal Waters. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology, Washington, DC, 154 pp. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/hypoxia-report.pdf

81. Barton, A., G.G. Waldbusser, R.A. Feely, S.B. Weisberg, J.A. Newton, B. Hales, S. Cudd, B. Eudeline, C.J. Langdon, I. Jefferds, T. King, A. Suhrbier, and K. McLaughli, 2015: Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography*, **28** (2), 146–159. https://doi.org/10.5670/oceanog.2015.38

82. Gomez, F.A., R. Wanninkhof, L. Barbero, S.K. Lee, and F.J. Hernandez Jr, 2020: Seasonal patterns of surface inorganic carbon system variables in the Gulf of Mexico inferred from a regional high-resolution ocean biogeochemical model. *Biogeosciences*, **17** (6), 1685–1700. https://doi.org/10.5194/bg-17-1685-2020

83. Xu, Y.-Y., W.-J. Cai, R. Wanninkhof, J. Salisbury, J. Reimer, and B. Chen, 2020: Long-term changes of carbonate chemistry variables along the North American East Coast. *Journal of Geophysical Research: Oceans*, **125** (7), e2019JC015982. https://doi.org/10.1029/2019jc015982

84. Mahoney, A.R., H. Eicken, A.G. Gaylord, and R. Gens, 2014: Landfast sea ice extent in the Chukchi and Beaufort Seas: The annual cycle and decadal variability. *Cold Regions Science and Technology*, **103**, 41–56. https://doi.org/10.1016/j.coldregions.2014.03.003

85. Thoman, R.L., U.S. Bhatt, P.A. Bieniek, B.R. Brettschneider, M. Brubaker, S.L. Danielson, Z. Labe, R. Lader, W.N. Meier, G. Sheffield, and J.E. Walsh, 2020: The record low Bering Sea ice extent in 2018: Context, impacts, and an assessment of the role of anthropogenic climate change. *Bulletin of the American Meteorological Society*, **101** (1), S53–S58. https://doi.org/10.1175/bams-d-19-0175.1

86. Dauginis, A.A. and L.C. Brown, 2021: Recent changes in pan-Arctic sea ice, lake ice, and snow-on/off timing. *The Cryosphere*, **15** (10), 4781–4805. https://doi.org/10.5194/tc-15-4781-2021

87. Imrit, M.A. and S. Sharma, 2021: Climate change is contributing to faster rates of lake ice loss in lakes around the Northern Hemisphere. *Journal of Geophysical Research: Biogeosciences*, **126** (7), e2020JG006134. https://doi.org/10.1029/2020jg006134

88. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

89. Sharmila, S. and K.J.E. Walsh, 2018: Recent poleward shift of tropical cyclone formation linked to Hadley cell expansion. *Nature Climate Change*, **8** (8), 730–736. https://doi.org/10.1038/s41558-018-0227-5

90. Lian, T., J. Ying, H.-L. Ren, C. Zhang, T. Liu, and X.-X. Tan, 2019: Effects of tropical cyclones on ENSO. *Journal of Climate*, **32** (19), 6423–6443. https://doi.org/10.1175/jcli-d-18-0821.1

91. Wang, Q. and J. Li, 2022: Feedback of tropical cyclones on El Niño diversity. Part I: Phenomenon. *Climate Dynamics*, **59**, 169–184. https://doi.org/10.1007/s00382-021-06122-y

92. Wang, Q., J. Li, F.-F. Jin, J.C.L. Chan, C. Wang, R. Ding, C. Sun, F. Zheng, J. Feng, F. Xie, Y. Li, F. Li, and Y. Xu, 2019: Tropical cyclones act to intensify El Niño. *Nature Communications*, **10** (1), 3793. https://doi.org/10.1038/s41467-019-11720-w

93. Cai, W., A. Santoso, M. Collins, B. Dewitte, C. Karamperidou, J.-S. Kug, M. Lengaigne, M.J. McPhaden, M.F. Stuecker, A.S. Taschetto, A. Timmermann, L. Wu, S.-W. Yeh, G. Wang, B. Ng, F. Jia, Y. Yang, J. Ying, X.-T. Zheng, T. Bayr, J.R. Brown, A. Capotondi, K.M. Cobb, B. Gan, T. Geng, Y.-G. Ham, F.-F. Jin, H.-S. Jo, X. Li, X. Lin, S. McGregor, J.-H. Park, K. Stein, K. Yang, L. Zhang, and W. Zhong, 2021: Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment*, **2** (9), 628–644. https://doi.org/10.1038/s43017-021-00199-z

94. Cook, B.I., A.P. Williams, J.S. Mankin, R. Seager, J.E. Smerdon, and D. Singh, 2018: Revisiting the leading drivers of Pacific coastal drought variability in the contiguous United States. *Journal of Climate*, **31** (1), 25–43. https://doi.org/10.1175/jcli-d-17-0172.1

95. Jong, B.-T., M. Ting, and R. Seager, 2021: Assessing ENSO summer teleconnections, impacts, and predictability in North America. *Journal of Climate*, **34** (9), 3629–3643. https://doi.org/10.1175/jcli-d-20-0761.1

96. Murphy, B.F., S.B. Power, and S. McGree, 2014: The varied impacts of El Niño–Southern Oscillation on Pacific island climates. *Journal of Climate*, **27** (11), 4015–4036. https://doi.org/10.1175/jcli-d-13-00130.1

97. Lin, I.-I., S.J. Camargo, C.M. Patricola, J. Boucharel, S. Chand, P. Klotzbach, J.C.L. Chan, B. Wang, P. Chang, T. Li, and F.-F. Jin, 2020: Ch. 17. ENSO and tropical cyclones. In: *El Niño Southern Oscillation in a Changing Climate*. McPhaden, M.J., A. Santoso, and W. Cai, Eds. American Geophysical Union, 377–408. https://doi.org/10.1002/9781119548164.ch17

98. Algarra, I., R. Nieto, A.M. Ramos, J. Eiras-Barca, R.M. Trigo, and L. Gimeno, 2020: Significant increase of global anomalous moisture uptake feeding landfalling atmospheric rivers. *Nature Communications*, **11** (1), 5082. https://doi.org/10.1038/s41467-020-18876-w

99. Hu, H. and F. Dominguez, 2019: Understanding the role of tropical moisture in atmospheric rivers. *Journal of Geophysical Research: Atmospheres*, **124** (24), 13826–13842. https://doi.org/10.1029/2019jd030867

100. Larour, E., E.R. Ivins, and S. Adhikari, 2017: Should coastal planners have concern over where land ice is melting? *Science Advances*, **3** (11), e1700537. https://doi.org/10.1126/sciadv.1700537

101. Mitrovica, J.X., C.C. Hay, R.E. Kopp, C. Harig, and K. Latychev, 2018: Quantifying the sensitivity of sea level change in coastal localities to the geometry of polar ice mass flux. *Journal of Climate*, **31** (9), 3701–3709. https://doi.org/10.1175/jcli-d-17-0465.1

102. DeConto, R.M., D. Pollard, R.B. Alley, I. Velicogna, E. Gasson, N. Gomez, S. Sadai, A. Condron, D.M. Gilford, E.L. Ashe, R.E. Kopp, D. Li, and A. Dutton, 2021: The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature*, **593** (7857), 83–89. https://doi.org/10.1038/s41586-021-03427-0

103. Gilford, D.M., E.L. Ashe, R.M. DeConto, R.E. Kopp, D. Pollard, and A. Rovere, 2020: Could the last interglacial constrain projections of future Antarctic ice mass loss and sea-level rise? *Journal of Geophysical Research: Earth Surface*, **125** (10), e2019JF005418. https://doi.org/10.1029/2019jf005418

104. Dutton, A., A.E. Carlson, A.J. Long, G.A. Milne, P.U. Clark, R. DeConto, B.P. Horton, S. Rahmstorf, and M.E. Raymo, 2015: Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science*, **349** (6244), 4019. https://doi.org/10.1126/science.aaa4019

105. Coumou, D., G. Di Capua, S. Vavrus, L. Wang, and S. Wang, 2018: The influence of Arctic amplification on mid-latitude summer circulation. *Nature Communications*, **9** (1), 2959. https://doi.org/10.1038/s41467-018-05256-8

106. Francis, J.A., N. Skific, and S.J. Vavrus, 2018: North American weather regimes are becoming more persistent: Is Arctic amplification a factor? *Geophysical Research Letters*, **45** (20), 11414–11422. https://doi.org/10.1029/2018gl080252

107. Kornhuber, K. and T. Tamarin-Brodsky, 2021: Future changes in Northern Hemisphere summer weather persistence linked to projected Arctic warming. *Geophysical Research Letters*, **48** (4), e2020GL091603. https://doi.org/10.1029/2020gl091603

108. Blackport, R., J.A. Screen, K. van der Wiel, and R. Bintanja, 2019: Minimal influence of reduced Arctic sea ice on coincident cold winters in mid-latitudes. *Nature Climate Change*, **9** (9), 697–704. https://doi.org/10.1038/s41558-019-0551-4

109. Cohen, J., X. Zhang, J. Francis, T. Jung, R. Kwok, J. Overland, T.J. Ballinger, U.S. Bhatt, H.W. Chen, D. Coumou, S. Feldstein, H. Gu, D. Handorf, G. Henderson, M. Ionita, M. Kretschmer, F. Laliberte, S. Lee, H.W. Linderholm, W. Maslowski, Y. Peings, K. Pfeiffer, I. Rigor, T. Semmler, J. Stroeve, P.C. Taylor, S. Vavrus, T. Vihma, S. Wang, M. Wendisch, Y. Wu, and J. Yoon, 2020: Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather. *Nature Climate Change*, **10** (1), 20–29. https://doi.org/10.1038/s41558-019-0662-y

110. Cohen, J., L. Agel, M. Barlow, C.I. Garfinkel, and I. White, 2021: Linking Arctic variability and change with extreme winter weather in the United States. *Science*, **373** (6559), 1116–1121. https://doi.org/10.1126/science.abi9167

111. Cohen, J., K. Pfeiffer, and J.A. Francis, 2018: Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States. *Nature Communications*, **9** (1), 869. https://doi.org/10.1038/s41467-018-02992-9

112. Overland, J.E., T.J. Ballinger, J. Cohen, J.A. Francis, E. Hanna, R. Jaiser, B.M. Kim, S.J. Kim, J. Ukita, T. Vihma, M. Wang, and X. Zhang, 2021: How do intermittency and simultaneous processes obfuscate the Arctic influence on midlatitude winter extreme weather events? *Environmental Research Letters*, **16** (4), 043002. https://doi.org/10.1088/1748-9326/abdb5d

113. Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner, 2017: Ch. 6. Temperature changes in the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 185–206. https://doi.org/10.7930/j0n29v45

114. Rogers, C.D.W., M. Ting, C. Li, K. Kornhuber, E.D. Coffel, R.M. Horton, C. Raymond, and D. Singh, 2021: Recent increases in exposure to extreme humid-heat events disproportionately affect populated regions. *Geophysical Research Letters*, **48** (19), e2021GL094183. https://doi.org/10.1029/2021gl094183

115. Keellings, D. and H. Moradkhani, 2020: Spatiotemporal evolution of heat wave severity and coverage across the United States. *Geophysical Research Letters*, **47** (9), e2020GL087097. https://doi.org/10.1029/2020gl087097

116. Lyon, B. and A.G. Barnston, 2017: Diverse characteristics of U.S. summer heat waves. *Journal of Climate*, **30** (19), 7827–7845. https://doi.org/10.1175/jcli-d-17-0098.1

117. Rogers, C.D.W., K. Kornhuber, S.E. Perkins-Kirkpatrick, P.C. Loikith, and D. Singh, 2022: Sixfold increase in historical Northern Hemisphere concurrent large heatwaves driven by warming and changing atmospheric circulations. *Journal of Climate*, **35** (3), 1063–1078. https://doi.org/10.1175/jcli-d-21-0200.1

118. USGCRP, 2023: USGCRP Indicators Platform: Heat Waves. U.S. Global Change Research Program. https://www.globalchange.gov/indicators/heat-waves

119. Cooley, S., D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehiwet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, and M. Skern-Mauritzen, 2022: Ch. 3. Oceans and coastal ecosystems and their services. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 379–550. https://doi.org/10.1017/9781009325844.005

120. Smith, E.T. and S.C. Sheridan, 2020: Where do cold air outbreaks occur, and how have they changed over time? *Geophysical Research Letters*, **47** (13), e2020GL086983. https://doi.org/10.1029/2020gl086983

121. van Oldenborgh, G.J., E. Mitchell-Larson, G.A. Vecchi, H. de Vries, R. Vautard, and F. Otto, 2019: Cold waves are getting milder in the northern midlatitudes. *Environmental Research Letters*, **14** (11), 114004. https://doi.org/10.1088/1748-9326/ab4867

122. Tuholske, C., K. Caylor, C. Funk, A. Verdin, S. Sweeney, K. Grace, P. Peterson, and T. Evans, 2021: Global urban population exposure to extreme heat. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (41), e2024792118. https://doi.org/10.1073/pnas.2024792118

123. Davenport, F.V., M. Burke, and N.S. Diffenbaugh, 2021: Contribution of historical precipitation change to US flood damages. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (4), e2017524118. https://doi.org/10.1073/pnas.2017524118

124. Mallakpour, I. and G. Villarini, 2015: The changing nature of flooding across the central United States. *Nature Climate Change*, **5** (3), 250–254. https://doi.org/10.1038/nclimate2516

125. Dunn, R.J.H., L.V. Alexander, M.G. Donat, X. Zhang, M. Bador, N. Herold, T. Lippmann, R. Allan, E. Aguilar, A.A. Barry, M. Brunet, J. Caesar, G. Chagnaud, V. Cheng, T. Cinco, I. Durre, R. de Guzman, T.M. Htay, W.M. Wan Ibadullah, M.K.I. Bin Ibrahim, M. Khoshkam, A. Kruger, H. Kubota, T.W. Leng, G. Lim, L. Li-Sha, J. Marengo, S. Mbatha, S. McGree, M. Menne, M. de los Milagros Skansi, S. Ngwenya, F. Nkrumah, C. Oonariya, J.D. Pabon-Caicedo, G. Panthou, C. Pham, F. Rahimzadeh, A. Ramos, E. Salgado, J. Salinger, Y. Sané, A. Sopaheluwakan, A. Srivastava, Y. Sun, B. Timbal, N. Trachow, B. Trewin, G. van der Schrier, J. Vazquez-Aguirre, R. Vasquez, C. Villarroel, L. Vincent, T. Vischel, R. Vose, and M.N.A. Bin Hj Yussof, 2020: Development of an updated global land in situ-based data set of temperature and precipitation extremes: HadEX3. *Journal of Geophysical Research: Atmospheres*, **125** (16), e2019JD032263. https://doi.org/10.1029/2019jd032263

126. Diffenbaugh, N.S., D. Singh, and J.S. Mankin, 2018: Unprecedented climate events: Historical changes, aspirational targets, and national commitments. *Science Advances*, **4** (2), 3354. https://doi.org/10.1126/sciadv.aao3354

127. Kirchmeier-Young, M.C. and X. Zhang, 2020: Human influence has intensified extreme precipitation in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (24), 13308–13313. https://doi.org/10.1073/pnas.1921628117

128. Pederson, N., A.R. Bell, E.R. Cook, U. Lall, N. Devineni, R. Seager, K. Eggleston, and K.P. Vranes, 2013: Is an epic pluvial masking the water insecurity of the Greater New York City region? *Journal of Climate*, **26** (4), 1339–1354. https://doi.org/10.1175/jcli-d-11-00723.1

129. McEwan, R.W., J.M. Dyer, and N. Pederson, 2011: Multiple interacting ecosystem drivers: Toward an encompassing hypothesis of oak forest dynamics across eastern North America. *Ecography*, **34** (2), 244–256. https://doi.org/10.1111/j.1600-0587.2010.06390.x

130. Pederson, N., A.W. D'Amato, J.M. Dyer, D.R. Foster, D. Goldblum, J.L. Hart, A.E. Hessl, L.R. Iverson, S.T. Jackson, D. Martin-Benito, B.C. McCarthy, R.W. McEwan, D.J. Mladenoff, A.J. Parker, B. Shuman, and J.W. Williams, 2015: Climate remains an important driver of post-European vegetation change in the eastern United States. *Global Change Biology*, **21** (6), 2105–2110. https://doi.org/10.1111/gcb.12779

131. Easterling, D.R., K.E. Kunkel, J.R. Arnold, T. Knutson, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner, 2017: Precipitation change in the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 207–230. https://doi.org/10.7930/J0H993CC

132. Wilhite, D.A. and M.H. Glantz, 1985: Understanding: The drought phenomenon: The role of definitions. *Water International*, **10** (3), 111–120. https://doi.org/10.1080/02508068508686328

133. Udall, B. and J. Overpeck, 2017: The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, **53** (3), 2404–2418. https://doi.org/10.1002/2016wr019638

134. Milly, P.C.D. and K.A. Dunne, 2020: Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. *Science*, **367** (6483), 1252–1255. https://doi.org/10.1126/science.aay9187

135. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. https://doi.org/10.1038/s41558-022-01290-z

136. Albano, C.M., J.T. Abatzoglou, D.J. McEvoy, J.L. Huntington, C.G. Morton, M.D. Dettinger, and T.J. Ott, 2022: A Multidataset assessment of climatic drivers and uncertainties of recent trends in evaporative demand across the continental United States. *Journal of Hydrometeorology*, **23** (4), 505–519. https://doi.org/10.1175/jhm-d-21-0163.1

137. Diffenbaugh, N.S., D.L. Swain, and D. Touma, 2015: Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (13), 3931–3936. https://doi.org/10.1073/pnas.1422385112

138. Marvel, K., B.I. Cook, C. Bonfils, J.E. Smerdon, A.P. Williams, and H. Liu, 2021: Projected changes to hydroclimate seasonality in the continental United States. *Earth's Future*, **9** (9), e2021EF002019. https://doi.org/10.1029/2021ef002019

139. Andreadis, K.M. and D.P. Lettenmaier, 2006: Trends in 20th century drought over the continental United States. *Geophysical Research Letters*, **33** (10), L10403. https://doi.org/10.1029/2006gl025711

140. Overpeck, J.T. and B. Udall, 2020: Climate change and the aridification of North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (22), 11856–11858. https://doi.org/10.1073/pnas.2006323117

141. Stevenson, S., S. Coats, D. Touma, J. Cole, F. Lehner, J. Fasullo, and B. Otto-Bliesner, 2022: Twenty-first century hydroclimate: A continually changing baseline, with more frequent extremes. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (12), e2108124119. https://doi.org/10.1073/pnas.2108124119

142. Swain, D.L., B. Langenbrunner, J.D. Neelin, and A. Hall, 2018: Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change*, **8** (5), 427–433. https://doi.org/10.1038/s41558-018-0140-y

143. Su, L., Q. Cao, M. Xiao, D.M. Mocko, M. Barlage, D. Li, C.D. Peters-Lidard, and D.P. Lettenmaier, 2021: Drought variability over the conterminous United States for the past century. *Journal of Hydrometeorology*, **22** (5), 1153–1168. https://doi.org/10.1175/jhm-d-20-0158.1

144. McCabe, G.J., D.M. Wolock, and S.H. Austin, 2017: Variability of runoff-based drought conditions in the conterminous United States. *International Journal of Climatology*, **37** (2), 1014–1021. https://doi.org/10.1002/joc.4756

145. Krakauer, N.Y., T. Lakhankar, and D. Hudson, 2019: Trends in drought over the northeast United States. *Water*, **11** (9), 1834. https://doi.org/10.3390/w11091834

146. Otkin, J.A., M. Svoboda, E.D. Hunt, T.W. Ford, M.C. Anderson, C. Hain, and J.B. Basara, 2018: Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bulletin of the American Meteorological Society*, **99** (5), 911–919. https://doi.org/10.1175/bams-d-17-0149.1

147. Otkin, J.A., M. Woloszyn, H. Wang, M. Svoboda, M. Skumanich, R. Pulwarty, J. Lisonbee, A. Hoell, M. Hobbins, T. Haigh, and A.E. Cravens, 2022: Getting ahead of flash drought: From early warning to early action. *Bulletin of the American Meteorological Society*, **103** (10), E2188–E2202. https://doi.org/10.1175/bams-d-21-0288.1

148. Pendergrass, A.G., G.A. Meehl, R. Pulwarty, M. Hobbins, A. Hoell, A. AghaKouchak, C.J.W. Bonfils, A.J.E. Gallant, M. Hoerling, D. Hoffmann, L. Kaatz, F. Lehner, D. Llewellyn, P. Mote, R.B. Neale, J.T. Overpeck, A. Sheffield, K. Stahl, M. Svoboda, M.C. Wheeler, A.W. Wood, and C.A. Woodhouse, 2020: Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nature Climate Change*, **10**, 191–199. https://doi.org/10.1038/s41558-020-0709-0

149. Qing, Y., S. Wang, B.C. Ancell, and Z.-L. Yang, 2022: Accelerating flash droughts induced by the joint influence of soil moisture depletion and atmospheric aridity. *Nature Communications*, **13** (1), 1139. https://doi.org/10.1038/s41467-022-28752-4

150. Gonzales, K.R., D.L. Swain, K.M. Nardi, E.A. Barnes, and N.S. Diffenbaugh, 2019: Recent warming of landfalling atmospheric rivers along the West Coast of the United States. *Journal of Geophysical Research: Atmospheres*, **124** (13), 6810–6826. https://doi.org/10.1029/2018jd029860

151. Gershunov, A., T. Shulgina, F.M. Ralph, D.A. Lavers, and J.J. Rutz, 2017: Assessing the climate-scale variability of atmospheric rivers affecting western North America. *Geophysical Research Letters*, **44** (15), 7900–7908. https://doi.org/10.1002/2017gl074175

152. Knutson, T., S.J. Camargo, J.C.L. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2019: Tropical cyclones and climate change assessment: Part I: Detection and attribution. *Bulletin of the American Meteorological Society*, **100** (10), 1987–2007. https://doi.org/10.1175/bams-d-18-0189.1

153. Vecchi, G.A., C. Landsea, W. Zhang, G. Villarini, and T. Knutson, 2021: Changes in Atlantic major hurricane frequency since the late-19th century. *Nature Communications*, **12** (1), 4054. https://doi.org/10.1038/s41467-021-24268-5

154. Bhatia, K.T., G.A. Vecchi, T.R. Knutson, H. Murakami, J. Kossin, K.W. Dixon, and C.E. Whitlock, 2019: Recent increases in tropical cyclone intensification rates. *Nature Communications*, **10** (1), 635. https://doi.org/10.1038/s41467-019-08471-z

155. Kishtawal, C.M., N. Jaiswal, R. Singh, and D. Niyogi, 2012: Tropical cyclone intensification trends during satellite era (1986–2010). *Geophysical Research Letters*, **39** (10). https://doi.org/10.1029/2012gl051700

156. Li, L. and P. Chakraborty, 2020: Slower decay of landfalling hurricanes in a warming world. *Nature*, **587** (7833), 230–234. https://doi.org/10.1038/s41586-020-2867-7

157. Kossin, J.P., 2019: Reply to: Moon, I.-J. et al.; Lanzante, J. R. *Nature*, **570** (7759), E16–E22. https://doi.org/10.1038/s41586-019-1224-1

158. Hall, T.M. and J.P. Kossin, 2019: Hurricane stalling along the North American coast and implications for rainfall. *npj Climate and Atmospheric Science*, **2** (1), 1–9. https://doi.org/10.1038/s41612-019-0074-8

159. Grinsted, A., P. Ditlevsen, and J.H. Christensen, 2019: Normalized US hurricane damage estimates using area of total destruction, 1900–2018. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (48), 23942–23946. https://doi.org/10.1073/pnas.1912277116

160. Taszarek, M., J.T. Allen, H.E. Brooks, N. Pilguj, and B. Czernecki, 2021: Differing trends in United States and European severe thunderstorm environments in a warming climate. *Bulletin of the American Meteorological Society*, **102** (2), E296–E322. https://doi.org/10.1175/bams-d-20-0004.1

161. Tippett, M.K., C. Lepore, and J.E. Cohen, 2016: More tornadoes in the most extreme U.S. tornado outbreaks. *Science*, **354** (6318), 1419–1423. https://doi.org/10.1126/science.aah7393

162. Elsner, J.B., T. Fricker, and Z. Schroder, 2019: Increasingly powerful tornadoes in the United States. *Geophysical Research Letters*, **46** (1), 392–398. https://doi.org/10.1029/2018gl080819

163. Moore, T.W., 2018: Annual and seasonal tornado trends in the contiguous United States and its regions. *International Journal of Climatology*, **38** (3), 1582–1594. https://doi.org/10.1002/joc.5285

164. Gensini, V.A. and H.E. Brooks, 2018: Spatial trends in United States tornado frequency. *npj Climate and Atmospheric Science*, **1** (1), 38. https://doi.org/10.1038/s41612-018-0048-2

165. Hu, H., L.R. Leung, and Z. Feng, 2020: Observed warm-season characteristics of MCS and Non-MCS rainfall and their recent changes in the central United States. *Geophysical Research Letters*, **47** (6), e2019GL086783. https://doi.org/10.1029/2019gl086783

166. Allen, J.T. and M.K. Tippett, 2015: The characteristics of United States hail reports: 1955–2014. *E-Journal of Severe Storms Meteorology*, **10** (3). https://doi.org/10.55599/ejssm.v10i3.60

167. Füllekrug, M., E. Williams, C. Price, S. Goodman, R. Holzworth, K. Virts, and D. Buechler, 2022: Sidebar 2.1: Lightning [in State of the Climate 2021]. *Bulletin of the American Meteorological Society*, **103** (8). https://doi.org/10.1175/2022bamsstateoftheclimate.1

168. Tang, B.H., V.A. Gensini, and C.R. Homeyer, 2019: Trends in United States large hail environments and observations. *Climate and Atmospheric Science*, **2** (1), 1–7. https://doi.org/10.1038/s41612-019-0103-7

169. Higuera, P.E. and J.T. Abatzoglou, 2021: Record-setting climate enabled the extraordinary 2020 fire season in the western United States. *Global Change Biology*, **27** (1), 1–2. https://doi.org/10.1111/gcb.15388

170. Carter, V.A., A. Brunelle, M.J. Power, R.J. DeRose, M.F. Bekker, I. Hart, S. Brewer, J. Spangler, E. Robinson, M. Abbott, S.Y. Maezumi, and B.F. Codding, 2021: Legacies of Indigenous land use shaped past wildfire regimes in the Basin-Plateau Region, USA. *Communications Earth & Environment*, **2** (1), 72. https://doi.org/10.1038/s43247-021-00137-3

171. Higuera, P.E., B.N. Shuman, and K.D. Wolf, 2021: Rocky Mountain subalpine forests now burning more than any time in recent millennia. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (25), e2103135118. https://doi.org/10.1073/pnas.2103135118

172. Hessburg, P.F., C.L. Miller, S.A. Parks, N.A. Povak, A.H. Taylor, P.E. Higuera, S.J. Prichard, M.P. North, B.M. Collins, M.D. Hurteau, A.J. Larson, C.D. Allen, S.L. Stephens, H. Rivera-Huerta, C.S. Stevens-Rumann, L.D. Daniels, Z.e. Gedalof, R.W. Gray, V.R. Kane, D.J. Churchill, R.K. Hagmann, T.A. Spies, C.A. Cansler, R.T. Belote, T.T. Veblen, M.A. Battaglia, C. Hoffman, C.N. Skinner, H.D. Safford, and R.B. Salter, 2019: Climate, environment, and disturbance history govern resilience of western North American forests. *Frontiers in Ecology and Evolution*, **7**, 239. https://doi.org/10.3389/fevo.2019.00239

173. Zhuang, Y., R. Fu, B.D. Santer, R.E. Dickinson, and A. Hall, 2021: Quantifying contributions of natural variability and anthropogenic forcings on increased fire weather risk over the western United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (45), e2111875118. https://doi.org/10.1073/pnas.2111875118

174. Calder, W.J. and B. Shuman, 2017: Extensive wildfires, climate change, and an abrupt state change in subalpine ribbon forests, Colorado. *Ecology*, **98** (10), 2585–2600. https://doi.org/10.1002/ecy.1959

175. Balch, J.K., B.A. Bradley, J.T. Abatzoglou, R.C. Nagy, E.J. Fusco, and A.L. Mahood, 2017: Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (11), 2946–2951. https://doi.org/10.1073/pnas.1617394114

176. Cattau, M.E., C. Wessman, A. Mahood, and J.K. Balch, 2020: Anthropogenic and lightning-started fires are becoming larger and more frequent over a longer season length in the U.S.A. *Global Ecology and Biogeography*, **29** (4), 668–681. https://doi.org/10.1111/geb.13058

177. Radeloff, V.C., D.P. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar-Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, and S.I. Stewart, 2018: Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (13), 3314–3319. https://doi.org/10.1073/pnas.1718850115

178. Kalashnikov, D.A., J.T. Abatzoglou, N.J. Nauslar, D.L. Swain, D. Touma, and D. Singh, 2022: Meteorological and geographical factors associated with dry lightning in central and northern California. *Environmental Research: Climate*, **1** (2), 025001. https://doi.org/10.1088/2752-5295/ac84a0

179. Villarini, G. and J.A. Smith, 2013: Spatial and temporal variability of cloud-to-ground lightning over the continental U.S. during the period 1995–2010. *Atmospheric Research*, **124**, 137–148. https://doi.org/10.1016/j.atmosres.2012.12.017

180. Lyon, B., A.G. Barnston, E. Coffel, and R.M. Horton, 2019: Projected increase in the spatial extent of contiguous US summer heat waves and associated attributes. *Environmental Research Letters*, **14** (11), 114029. https://doi.org/10.1088/1748-9326/ab4b41

181. Baek, S.H. and J.M. Lora, 2021: Counterbalancing influences of aerosols and greenhouse gases on atmospheric rivers. *Nature Climate Change*, **11** (11), 958–965. https://doi.org/10.1038/s41558-021-01166-8

182. Huang, X., D.L. Swain, and A.D. Hall, 2020: Future precipitation increase from very high resolution ensemble downscaling of extreme atmospheric river storms in California. *Science Advances*, **6** (29), 1323. https://doi.org/10.1126/sciadv.aba1323

183. Knutson, T., S.J. Camargo, J.C.L. Chan, K. Emanuel, C.H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2020: Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, **101** (3), 303–322. https://doi.org/10.1175/bams-d-18-0194.1

184. Payne, A.E., M.-E. Demory, L.R. Leung, A.M. Ramos, C.A. Shields, J.J. Rutz, N. Siler, G. Villarini, A. Hall, and F.M. Ralph, 2020: Responses and impacts of atmospheric rivers to climate change. *Nature Reviews Earth & Environment*, **1** (3), 143–157. https://doi.org/10.1038/s43017-020-0030-5

185. Swain, D.L., O.E.J. Wing, P.D. Bates, J.M. Done, K.A. Johnson, and D.R. Cameron, 2020: Increased flood exposure due to climate change and population growth in the United States. *Earth's Future*, **8** (11), e2020EF001778. https://doi.org/10.1029/2020ef001778

186. Akinsanola, A.A., G.J. Kooperman, K.A. Reed, A.G. Pendergrass, and W.M. Hannah, 2020: Projected changes in seasonal precipitation extremes over the United States in CMIP6 simulations. *Environmental Research Letters*, **15** (10), 104078. https://doi.org/10.1088/1748-9326/abb397

187. Lachniet, M.S., Y. Asmerom, V. Polyak, and R. Denniston, 2020: Great Basin paleoclimate and aridity linked to Arctic warming and tropical Pacific sea surface temperatures. *Paleoceanography and Paleoclimatology*, **35** (7), e2019PA003785. https://doi.org/10.1029/2019pa003785

188. Cook, B.I., J.S. Mankin, A.P. Williams, K.D. Marvel, J.E. Smerdon, and H. Liu, 2021: Uncertainties, limits, and benefits of climate change mitigation for soil moisture drought in southwestern North America. *Earth's Future*, **9** (9), e2021EF002014. https://doi.org/10.1029/2021ef002014

189. Lehner, F., A.W. Wood, J.A. Vano, D.M. Lawrence, M.P. Clark, and J.S. Mankin, 2019: The potential to reduce uncertainty in regional runoff projections from climate models. *Nature Climate Change*, **9** (12), 926–933. https://doi.org/10.1038/s41558-019-0639-x

190. Cook, B.I., T.R. Ault, and J.E. Smerdon, 2015: Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances*, **1** (1), e1400082. https://doi.org/10.1126/sciadv.1400082

191. Sena, A.C.T., C.M. Patricola, and B. Loring, 2022: Future changes in active and inactive Atlantic hurricane seasons in the energy exascale Earth system model. *Geophysical Research Letters*, **49** (21), e2022GL100267. https://doi.org/10.1029/2022gl100267

192. Knutson, T.R., J.J. Sirutis, M.A. Bender, R.E. Tuleya, and B.A. Schenkel, 2022: Dynamical downscaling projections of late twenty-first-century U.S. landfalling hurricane activity. *Climatic Change*, **171** (3), 28. https://doi.org/10.1007/s10584-022-03346-7

193. Zhang, G., H. Murakami, T.R. Knutson, R. Mizuta, and K. Yoshida, 2020: Tropical cyclone motion in a changing climate. *Science Advances*, **6** (17), 7610. https://doi.org/10.1126/sciadv.aaz7610

194. Jing, R., N. Lin, K. Emanuel, G. Vecchi, and T.R. Knutson, 2021: A comparison of tropical cyclone projections in a high-resolution global climate model and from downscaling by statistical and statistical-deterministic methods. *Journal of Climate*, **34** (23), 9349–9364. https://doi.org/10.1175/jcli-d-21-0071.1

195. Gori, A., N. Lin, D. Xi, and K. Emanuel, 2022: Tropical cyclone climatology change greatly exacerbates US extreme rainfall–surge hazard. *Nature Climate Change*, **12** (2), 171–178. https://doi.org/10.1038/s41558-021-01272-7

196. Espinoza, V., D.E. Waliser, B. Guan, D.A. Lavers, and F.M. Ralph, 2018: Global analysis of climate change projection effects on atmospheric rivers. *Geophysical Research Letters*, **45** (9), 4299–4308. https://doi.org/10.1029/2017gl076968

197. Gershunov, A., T. Shulgina, R.E.S. Clemesha, K. Guirguis, D.W. Pierce, M.D. Dettinger, D.A. Lavers, D.R. Cayan, S.D. Polade, J. Kalansky, and F.M. Ralph, 2019: Precipitation regime change in western North America: The role of atmospheric rivers. *Scientific Reports*, **9** (1), 9944. https://doi.org/10.1038/s41598-019-46169-w

198. Rhoades, A.M., M.D. Risser, D.A. Stone, M.F. Wehner, and A.D. Jones, 2021: Implications of warming on western United States landfalling atmospheric rivers and their flood damages. *Weather and Climate Extremes*, **32**, 100326. https://doi.org/10.1016/j.wace.2021.100326

199. Lora, J.M., J.L. Mitchell, C. Risi, and A.E. Tripati, 2017: North Pacific atmospheric rivers and their influence on western North America at the Last Glacial Maximum. *Geophysical Research Letters*, **44** (2), 1051–1059. https://doi.org/10.1002/2016gl071541

200. Allen, J.T., 2018: Climate change and severe thunderstorms. In: *Oxford Research Encyclopedia of Climate Science*. Von Storch, H., Ed. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.62

201. Trapp, R.J., K.A. Hoogewind, and S. Lasher-Trapp, 2019: Future changes in hail occurrence in the United States determined through convection-permitting dynamical downscaling. *Journal of Climate*, **32** (17), 5493–5509. https://doi.org/10.1175/jcli-d-18-0740.1

202. Haberlie, A.M., W.S. Ashley, C.M. Battisto, and V.A. Gensini, 2022: Thunderstorm activity under intermediate and extreme climate change scenarios. *Geophysical Research Letters*, **49** (14), e2022GL098779. https://doi.org/10.1029/2022gl098779

203. Alizadeh, M.R., J. Adamowski, M.R. Nikoo, A. AghaKouchak, P. Dennison, and M. Sadegh, 2020: A century of observations reveals increasing likelihood of continental-scale compound dry-hot extremes. *Science Advances*, **6** (39), 4571. https://doi.org/10.1126/sciadv.aaz4571

204. Ridder, N.N., A.M. Ukkola, A.J. Pitman, and S.E. Perkins-Kirkpatrick, 2022: Increased occurrence of high impact compound events under climate change. *npj Climate and Atmospheric Science*, **5** (1), 3. https://doi.org/10.1038/s41612-021-00224-4

205. Mukherjee, S., A.K. Mishra, M.E. Mann, and C. Raymond, 2021: Anthropogenic warming and population growth may double US heat stress by the late 21st century. *Earth's Future*, **9** (5), e2020EF001886. https://doi.org/10.1029/2020ef001886

206. Coffel, E.D., R.M. Horton, and A. Sherbinin, 2018: Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century. *Environmental Research Letters*, **13** (1), 014001. https://doi.org/10.1088/1748-9326/aaa00e

207. Speizer, S., C. Raymond, C. Ivanovich, and R.M. Horton, 2022: Concentrated and intensifying humid heat extremes in the IPCC AR6 regions. *Geophysical Research Letters*, **49** (5), e2021GL097261. https://doi.org/10.1029/2021gl097261

208. Touma, D., S. Stevenson, D.L. Swain, D. Singh, D.A. Kalashnikov, and X. Huang, 2022: Climate change increases risk of extreme rainfall following wildfire in the western United States. *Science Advances*, **8** (13), 0320. https://doi.org/10.1126/sciadv.abm0320

209. Wahl, T., S. Jain, J. Bender, S.D. Meyers, and M.E. Luther, 2015: Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change*, **5** (12), 1093–1097. https://doi.org/10.1038/nclimate2736

210. Edwards, T.L., S. Nowicki, B. Marzeion, R. Hock, H. Goelzer, H. Seroussi, N.C. Jourdain, D.A. Slater, F.E. Turner, C.J. Smith, C.M. McKenna, E. Simon, A. Abe-Ouchi, J.M. Gregory, E. Larour, W.H. Lipscomb, A.J. Payne, A. Shepherd, C. Agosta, P. Alexander, T. Albrecht, B. Anderson, X. Asay-Davis, A. Aschwanden, A. Barthel, A. Bliss, R. Calov, C. Chambers, N. Champollion, Y. Choi, R. Cullather, J. Cuzzone, C. Dumas, D. Felikson, X. Fettweis, K. Fujita, B.K. Galton-Fenzi, R. Gladstone, N.R. Golledge, R. Greve, T. Hattermann, M.J. Hoffman, A. Humbert, M. Huss, P. Huybrechts, W. Immerzeel, T. Kleiner, P. Kraaijenbrink, S. Le clec'h, V. Lee, G.R. Leguy, C.M. Little, D.P. Lowry, J.-H. Malles, D.F. Martin, F. Maussion, M. Morlighem, J.F. O'Neill, I. Nias, F. Pattyn, T. Pelle, S.F. Price, A. Quiquet, V. Radić, R. Reese, D.R. Rounce, M. Rückamp, A. Sakai, C. Shafer, N.-J. Schlegel, S. Shannon, R.S. Smith, F. Straneo, S. Sun, L. Tarasov, L.D. Trusel, J. Van Breedam, R. van de Wal, M. van den Broeke, R. Winkelmann, H. Zekollari, C. Zhao, T. Zhang, and T. Zwinger, 2021: Projected land ice contributions to twenty-first-century sea level rise. *Nature*, **593** (7857), 74–82. https://doi.org/10.1038/s41586-021-03302-y

211. Robel, A.A., H. Seroussi, and G.H. Roe, 2019: Marine ice sheet instability amplifies and skews uncertainty in projections of future sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (30), 14887–14892. https://doi.org/10.1073/pnas.1904822116

212. Aschwanden, A., M.A. Fahnestock, M. Truffer, D.J. Brinkerhoff, R. Hock, C. Khroulev, R. Mottram, and S.A. Khan, 2019: Contribution of the Greenland ice sheet to sea level over the next millennium. *Science Advances*, **5** (6), 9396. https://doi.org/10.1126/sciadv.aav9396

213. Lowry, D.P., M. Krapp, N.R. Golledge, and A. Alevropoulos-Borrill, 2021: The influence of emissions scenarios on future Antarctic ice loss is unlikely to emerge this century. *Communications Earth & Environment*, **2** (1), 221. https://doi.org/10.1038/s43247-021-00289-2

214. Jones, T., J.K. Parrish, W.T. Peterson, E.P. Bjorkstedt, N.A. Bond, L.T. Ballance, V. Bowes, J.M. Hipfner, H.K. Burgess, J.E. Dolliver, K. Lindquist, J. Lindsey, H.M. Nevins, R.R. Robertson, J. Roletto, L. Wilson, T. Joyce, and J. Harvey, 2018: Massive mortality of a planktivorous seabird in response to a marine heatwave. *Geophysical Research Letters*, **45** (7), 3193–3202. https://doi.org/10.1002/2017gl076164

215. Siedlecki, S.A., J. Salisbury, D.K. Gledhill, C. Bastidas, S. Meseck, K. McGarry, C.W. Hunt, M. Alexander, D. Lavoie, Z.A. Wang, J. Scott, D.C. Brady, I. Mlsna, K. Azetsu-Scott, C.M. Liberti, D.C. Melrose, M.M. White, A. Pershing, D. Vandemark, D.W. Townsend, C. Chen, W. Mook, and R. Morrison, 2021: Projecting ocean acidification impacts for the Gulf of Maine to 2050: New tools and expectations. *Elementa: Science of the Anthropocene*, **9** (1), 00062. https://doi.org/10.1525/elementa.2020.00062

216. Gong, H., C. Li, and Y. Zhou, 2021: Emerging global ocean deoxygenation across the 21st century. *Geophysical Research Letters*, **48** (23), e2021GL095370. https://doi.org/10.1029/2021gl095370

217. Kwiatkowski, L., O. Torres, L. Bopp, O. Aumont, M. Chamberlain, J.R. Christian, J.P. Dunne, M. Gehlen, T. Ilyina, J.G. John, A. Lenton, H. Li, N.S. Lovenduski, J.C. Orr, J. Palmieri, Y. Santana-Falcón, J. Schwinger, R. Séférian, C.A. Stock, A. Tagliabue, Y. Takano, J. Tjiputra, K. Toyama, H. Tsujino, M. Watanabe, A. Yamamoto, A. Yool, and T. Ziehn, 2020: Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. *Biogeosciences*, **17** (13), 3439–3470. https://doi.org/10.5194/bg-17-3439-2020

218. Fischer, E.M., S. Sippel, and R. Knutti, 2021: Increasing probability of record-shattering climate extremes. *Nature Climate Change*, **11** (8), 689–695. https://doi.org/10.1038/s41558-021-01092-9

219. Hausfather, Z. and F.C. Moore, 2022: Net-zero commitments could limit warming to below 2 °C. *Nature*, **604** (7905), 247–248. https://doi.org/10.1038/d41586-022-00874-1

220. Hausfather, Z. and G.P. Peters, 2020: Emissions—The 'business as usual' story is misleading. *Nature*, **577** (7792), 618–620. https://doi.org/10.1038/d41586-020-00177-3

221. IEA, 2021: World Energy Outlook 2021. International Energy Agency, Paris, France. https://www.iea.org/reports/world-energy-outlook-2021

222. Meinshausen, M., J. Lewis, C. McGlade, J. Gütschow, Z. Nicholls, R. Burdon, L. Cozzi, and B. Hackmann, 2022: Realization of Paris Agreement pledges may limit warming just below 2 °C. *Nature*, **604** (7905), 304–309. https://doi.org/10.1038/s41586-022-04553-z

223. Sognnaes, I., A. Gambhir, D.-J. van de Ven, A. Nikas, A. Anger-Kraavi, H. Bui, L. Campagnolo, E. Delpiazzo, H. Doukas, S. Giarola, N. Grant, A. Hawkes, A.C. Köberle, A. Kolpakov, S. Mittal, J. Moreno, S. Perdana, J. Rogelj, M. Vielle, and G.P. Peters, 2021: A multi-model analysis of long-term emissions and warming implications of current mitigation efforts. *Nature Climate Change*, **11** (12), 1055–1062. https://doi.org/10.1038/s41558-021-01206-3

224. UNEP, 2021: Emissions Gap Report 2021: The Heat Is On–A World of Climate Promises Not Yet Delivered. United Nations Environment Programme, Nairobi, Kenya. https://www.unep.org/emissions-gap-report-2021

225. Ou, Y., G. Iyer, L. Clarke, J. Edmonds, A.A. Fawcett, N. Hultman, J.R. McFarland, M. Binsted, R. Cui, C. Fyson, A. Geiges, S. Gonzales-Zuñiga, M.J. Gidden, N. Höhne, L. Jeffery, T. Kuramochi, J. Lewis, M. Meinshausen, Z. Nicholls, P. Patel, S. Ragnauth, J. Rogelj, S. Waldhoff, S. Yu, and H. McJeon, 2021: Can updated climate pledges limit warming well below 2°C? *Science*, **374** (6568), 693–695. https://doi.org/10.1126/science.abl8976

226. Tong, D., Q. Zhang, Y. Zheng, K. Caldeira, C. Shearer, C. Hong, Y. Qin, and S.J. Davis, 2019: Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature*, **572** (7769), 373–377. https://doi.org/10.1038/s41586-019-1364-3

227. MacDougall, A.H., T.L. Frölicher, C.D. Jones, J. Rogelj, H.D. Matthews, K. Zickfeld, V.K. Arora, N.J. Barrett, V. Brovkin, F.A. Burger, M. Eby, A.V. Eliseev, T. Hajima, P.B. Holden, A. Jeltsch-Thömmes, C. Koven, N. Mengis, L. Menviel, M. Michou, I.I. Mokhov, A. Oka, J. Schwinger, R. Séférian, G. Shaffer, A. Sokolov, K. Tachiiri, J. Tjiputra, A. Wiltshire, and T. Ziehn, 2020: Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from $CO_2$. *Biogeosciences*, **17** (11), 2987–3016. https://doi.org/10.5194/bg-17-2987-2020

228. Thompson, P.R., M.J. Widlansky, B.D. Hamlington, M.A. Merrifield, J.J. Marra, G.T. Mitchum, and W. Sweet, 2021: Rapid increases and extreme months in projections of United States high-tide flooding. *Nature Climate Change*, **11** (7), 584–590. https://doi.org/10.1038/s41558-021-01077-8

229. Hamlington, B.D., T. Frederikse, P.R. Thompson, J.K. Willis, R.S. Nerem, and J.T. Fasullo, 2021: Past, present, and future Pacific sea-level change. *Earth's Future*, **9** (4), e2020EF001839. https://doi.org/10.1029/2020ef001839

230. Fisch-Romito, V., C. Guivarch, F. Creutzig, J.C. Minx, and M.W. Callaghan, 2021: Systematic map of the literature on carbon lock-in induced by long-lived capital. *Environmental Research Letters*, **16** (5), 053004. https://doi.org/10.1088/1748-9326/aba660

231. Roberts, C., F.W. Geels, M. Lockwood, P. Newell, H. Schmitz, B. Turnheim, and A. Jordan, 2018: The politics of accelerating low-carbon transitions: Towards a new research agenda. *Energy Research & Social Science*, **44**, 304–311. https://doi.org/10.1016/j.erss.2018.06.001

232. Sherwood, S.C., M.J. Webb, J.D. Annan, K.C. Armour, P.M. Forster, J.C. Hargreaves, G. Hegerl, S.A. Klein, K.D. Marvel, E.J. Rohling, M. Watanabe, T. Andrews, P. Braconnot, C.S. Bretherton, G.L. Foster, Z. Hausfather, A.S. von der Heydt, R. Knutti, T. Mauritsen, J.R. Norris, C. Proistosescu, M. Rugenstein, G.A. Schmidt, K.B. Tokarska, and M.D. Zelinka, 2020: An assessment of Earth's climate sensitivity using multiple lines of evidence. *Reviews of Geophysics*, **58** (4), e2019RG000678. https://doi.org/10.1029/2019rg000678

233. Gruber, N., D.C.E. Bakker, T. DeVries, L. Gregor, J. Hauck, P. Landschützer, G.A. McKinley, and J.D. Müller, 2023: Trends and variability in the ocean carbon sink. *Nature Reviews Earth & Environment*, **4** (2), 119–134. https://doi.org/10.1038/s43017-022-00381-x

234. Huntzinger, D.N., A. Chatterjee, D.J.P. Moore, S. Ohrel, T.O. West, B. Poulter, A.P. Walker, J. Dunne, S.R. Cooley, A.M. Michalak, M. Tzortziou, L. Bruhwiler, A. Rosenblatt, Y. Luo, P.J. Marcotullio, and J. Russell, 2018: Ch. 19. Future of the North American carbon cycle. In: *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*. Cavallaro, N., G. Shrestha, R. Birdsey, M.A. Mayes, R.G. Najjar, S.C. Reed, P. Romero-Lankao, and Z. Zhu, Eds. U.S. Global Change Research Program, Washington, DC, USA, 760–809. https://doi.org/10.7930/SOCCR2.2018.Ch19

235. O'Sullivan, M., P. Friedlingstein, S. Sitch, P. Anthoni, A. Arneth, V.K. Arora, V. Bastrikov, C. Delire, D.S. Goll, A. Jain, E. Kato, D. Kennedy, J. Knauer, S. Lienert, D. Lombardozzi, P.C. McGuire, J.R. Melton, J.E.M.S. Nabel, J. Pongratz, B. Poulter, R. Séférian, H. Tian, N. Vuichard, A.P. Walker, W. Yuan, X. Yue, and S. Zaehle, 2022: Process-oriented analysis of dominant sources of uncertainty in the land carbon sink. *Nature Communications*, **13** (1), 4781. https://doi.org/10.1038/s41467-022-32416-8

236. Cooley, S.R., D.J.P. Moore, S.R. Alin, D. Butman, D.W. Clow, N.H.F. French, R.A. Feely, Z.I. Johnson, G. Keppel-Aleks, S.E. Lohrenz, I.B. Ocko, E.H. Shadwick, A.J. Sutton, C.S. Potter, Y. Takatsuka, A.P. Walker, and R.M.S. Yu, 2018: Ch. 17. Biogeochemical effects of rising atmospheric carbon dioxide. In: *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*. Cavallaro, N., G. Shrestha, R. Birdsey, M.A. Mayes, R.G. Najjar, S.C. Reed, P. Romero-Lankao, and Z. Zhu, Eds. U.S. Global Change Research Program, Washington, DC, USA, 690–727. https://doi.org/10.7930/SOCCR2.2018.Ch17

237. Hugelius, G., J. Strauss, S. Zubrzycki, J.W. Harden, E.A.G. Schuur, C.L. Ping, L. Schirrmeister, G. Grosse, G.J. Michaelson, C.D. Koven, J.A. O'Donnell, B. Elberling, U. Mishra, P. Camill, Z. Yu, J. Palmtag, and P. Kuhry, 2014: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, **11** (23), 6573–6593. https://doi.org/10.5194/bg-11-6573-2014

238. Schuur, E.A.G., R. Bracho, G. Celis, E.F. Belshe, C. Ebert, J. Ledman, M. Mauritz, E.F. Pegoraro, C. Plaza, H. Rodenhizer, V. Romanovsky, C. Schädel, D. Schirokauer, M. Taylor, J.G. Vogel, and E.E. Webb, 2021: Tundra underlain by thawing permafrost persistently emits carbon to the atmosphere over 15 years of measurements. *Journal of Geophysical Research: Biogeosciences*, **126** (6), e2020JG006044. https://doi.org/10.1029/2020jg006044

239. Schuur, E.A.G., B.W. Abbott, R. Commane, J. Ernakovich, E. Euskirchen, G. Hugelius, G. Grosse, M. Jones, C. Koven, V. Leshyk, D. Lawrence, M.M. Loranty, M. Mauritz, D. Olefeldt, S. Natali, H. Rodenhizer, V. Salmon, C. Schädel, J. Strauss, C. Treat, and M. Turetsky, 2022: Permafrost and climate change: Carbon cycle feedbacks from the warming Arctic. *Annual Review of Environment and Resources*, **47** (1), 343–371. https://doi.org/10.1146/annurev-environ-012220-011847

240. Wang, S., A. Foster, E.A. Lenz, J.D. Kessler, J.C. Stroeve, L.O. Anderson, M. Turetsky, R. Betts, S. Zou, W. Liu, W.R. Boos, and Z. Hausfather, 2023: Mechanisms and impacts of Earth system tipping elements. *Reviews of Geophysics*, **61** (1), e2021RG000757. https://doi.org/10.1029/2021rg000757

241. Armstrong McKay, D.I., A. Staal, J.F. Abrams, R. Winkelmann, B. Sakschewski, S. Loriani, I. Fetzer, S.E. Cornell, J. Rockström, and T.M. Lenton, 2022: Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, **377** (6611), 7950. https://doi.org/10.1126/science.abn7950

242. Kopp, R.E., R.L. Shwom, G. Wagner, and J. Yuan, 2016: Tipping elements and climate–economic shocks: Pathways toward integrated assessment. *Earth's Future*, **4**, 346–372. https://doi.org/10.1002/2016ef000362

243. Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105** (6), 1786–1793. https://doi.org/10.1073/pnas.0705414105

244. McSweeney, R., 2020: Explainer: Nine 'Tipping Points' that Could be Triggered by Climate Change. Carbon Brief, London, UK. https://www.carbonbrief.org/explainer-nine-tipping-points-that-could-be-triggered-by-climate-change/

245. Bassis, J.N., B. Berg, A.J. Crawford, and D.I. Benn, 2021: Transition to marine ice cliff instability controlled by ice thickness gradients and velocity. *Science*, **372** (6548), 1342–1344. https://doi.org/10.1126/science.abf6271

246. Clerc, F., B.M. Minchew, and M.D. Behn, 2019: Marine ice cliff instability mitigated by slow removal of ice shelves. *Geophysical Research Letters*, **46** (21), 12108–12116. https://doi.org/10.1029/2019gl084183

247. Zeitz, M., A. Levermann, and R. Winkelmann, 2020: Sensitivity of ice loss to uncertainty in flow law parameters in an idealized one-dimensional geometry. *The Cryosphere*, **14** (10), 3537–3550. https://doi.org/10.5194/tc-14-3537-2020

248. Mottram, R., N. Hansen, C. Kittel, J.M. van Wessem, C. Agosta, C. Amory, F. Boberg, W.J. van de Berg, X. Fettweis, A. Gossart, N.P.M. van Lipzig, E. van Meijgaard, A. Orr, T. Phillips, S. Webster, S.B. Simonsen, and N. Souverijns, 2021: What is the surface mass balance of Antarctica? An intercomparison of regional climate model estimates. *The Cryosphere*, **15** (8), 3751–3784. https://doi.org/10.5194/tc-15-3751-2021

249. Bell, R.E., W. Chu, J. Kingslake, I. Das, M. Tedesco, K.J. Tinto, C.J. Zappa, M. Frezzotti, A. Boghosian, and W.S. Lee, 2017: Antarctic ice shelf potentially stabilized by export of meltwater in surface river. *Nature*, **544** (7650), 344–348. https://doi.org/10.1038/nature22048

250. MacFerrin, M., H. Machguth, D. van As, C. Charalampidis, C.M. Stevens, A. Heilig, B. Vandecrux, P.L. Langen, R. Mottram, X. Fettweis, M.R. van den Broeke, W.T. Pfeffer, M.S. Moussavi, and W. Abdalati, 2019: Rapid expansion of Greenland's low-permeability ice slabs. *Nature*, **573** (7774), 403–407. https://doi.org/10.1038/s41586-019-1550-3

251. Schlegel, N.J., H. Seroussi, M.P. Schodlok, E.Y. Larour, C. Boening, D. Limonadi, M.M. Watkins, M. Morlighem, and M.R. van den Broeke, 2018: Exploration of Antarctic ice sheet 100-year contribution to sea level rise and associated model uncertainties using the ISSM framework. *The Cryosphere*, **12** (11), 3511–3534. https://doi.org/10.5194/tc-12-3511-2018

252. Nias, I.J., S.L. Cornford, T.L. Edwards, N. Gourmelen, and A.J. Payne, 2019: Assessing uncertainty in the dynamical ice response to ocean warming in the Amundsen Sea Embayment, West Antarctica. *Geophysical Research Letters*, **46** (20), 11253–11260. https://doi.org/10.1029/2019gl084941

253. Buchanan, M.K., R.E. Kopp, M. Oppenheimer, and C. Tebaldi, 2016: Allowances for evolving coastal flood risk under uncertain local sea-level rise. *Climatic Change*, **137** (3), 347–362. https://doi.org/10.1007/s10584-016-1664-7

254. Haasnoot, M., J. Kwadijk, J. van Alphen, D. Le Bars, B. van den Hurk, F. Diermanse, A. van der Spek, G.O. Essink, J. Delsman, and M. Mens, 2020: Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands. *Environmental Research Letters*, **15** (3), 034007. https://doi.org/10.1088/1748-9326/ab666c

255. Rogelj, J., A. Popp, K.V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, T. Hasegawa, G. Marangoni, V. Krey, E. Kriegler, K. Riahi, D.P. van Vuuren, J. Doelman, L. Drouet, J. Edmonds, O. Fricko, M. Harmsen, P. Havlík, F. Humpenöder, E. Stehfest, and M. Tavoni, 2018: Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, **8** (4), 325–332. https://doi.org/10.1038/s41558-018-0091-3

256. O'Neill, B., M. van Aalst, Z. Zaiton Ibrahim, L. Berrang Ford, S. Bhadwal, H. Buhaug, D. Diaz, K. Frieler, M. Garschagen, A. Magnan, G. Midgley, A. Mirzabaev, A. Thomas, and R. Warren, 2022: Ch. 16. Key risks across sectors and regions. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2411–2538. https://doi.org/10.1017/9781009325844.025

257. Menne, M.J., C.N. Williams, B.E. Gleason, J.J. Rennie, and J.H. Lawrimore, 2018: The Global Historical Climatology Network monthly temperature dataset, version 4. *Journal of Climate*, **31** (24), 9835–9854. https://doi.org/10.1175/jcli-d-18-0094.1

258. Rohde, R., R.A. Muller, R. Jacobsen, E. Muller, S. Perlmutter, A. Rosenfeld, J. Wurtele, D. Groom, and C. Wickham, 2013: A new estimate of the average Earth surface land temperature spanning 1753 to 2011. *Geoinformatics & Geostatistics: An Overview*, **1** (1). https://doi.org/10.4172/2327-4581.1000101

259. Kondo, M., P.K. Patra, S. Sitch, P. Friedlingstein, B. Poulter, F. Chevallier, P. Ciais, J.G. Canadell, A. Bastos, R. Lauerwald, L. Calle, K. Ichii, P. Anthoni, A. Arneth, V. Haverd, A.K. Jain, E. Kato, M. Kautz, R.M. Law, S. Lienert, D. Lombardozzi, T. Maki, T. Nakamura, P. Peylin, C. Rödenbeck, R. Zhuravlev, T. Saeki, H. Tian, D. Zhu, and T. Ziehn, 2020: State of the science in reconciling top-down and bottom-up approaches for terrestrial $CO_2$ budget. *Global Change Biology*, **26** (3), 1068–1084. https://doi.org/10.1111/gcb.14917

260. Xu, R., H. Tian, N. Pan, R.L. Thompson, J.G. Canadell, E.A. Davidson, C. Nevison, W. Winiwarter, H. Shi, S. Pan, J. Chang, P. Ciais, S.R.S. Dangal, A. Ito, R.B. Jackson, F. Joos, R. Lauerwald, S. Lienert, T. Maavara, D.B. Millet, P.A. Raymond, P. Regnier, F.N. Tubiello, N. Vuichard, K.C. Wells, C. Wilson, J. Yang, Y. Yao, S. Zaehle, and F. Zhou, 2021: Magnitude and uncertainty of nitrous oxide emissions from North America based on bottom-up and top-down approaches: Informing future research and national inventories. *Geophysical Research Letters*, **48** (23), e2021GL095264. https://doi.org/10.1029/2021gl095264

261. IPCC, 2006: *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Eggleston, S., L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, Eds. Institute for Global Environmental Strategies, Hayama, Japan. https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

262. Byrne, B., D.F. Baker, S. Basu, M. Bertolacci, K.W. Bowman, D. Carroll, A. Chatterjee, F. Chevallier, P. Ciais, N. Cressie, D. Crisp, S. Crowell, F. Deng, Z. Deng, N.M. Deutscher, M.K. Dubey, S. Feng, O.E. García, D.W.T. Griffith, B. Herkommer, L. Hu, A.R. Jacobson, R. Janardanan, S. Jeong, M.S. Johnson, D.B.A. Jones, R. Kivi, J. Liu, Z. Liu, S. Maksyutov, J.B. Miller, S.M. Miller, I. Morino, J. Notholt, T. Oda, C.W. O'Dell, Y.S. Oh, H. Ohyama, P.K. Patra, H. Peiro, C. Petri, S. Philip, D.F. Pollard, B. Poulter, M. Remaud, A. Schuh, M.K. Sha, K. Shiomi, K. Strong, C. Sweeney, Y. Té, H. Tian, V.A. Velazco, M. Vrekoussis, T. Warneke, J.R. Worden, D. Wunch, Y. Yao, J. Yun, A. Zammit-Mangion, and N. Zeng, 2023: National $CO_2$ budgets (2015–2020) inferred from atmospheric $CO_2$ observations in support of the global stocktake. *Earth System Science Data*, **15** (2), 963–1004. https://doi.org/10.5194/essd-15-963-2023

263. Ciais, P., A. Bastos, F. Chevallier, R. Lauerwald, B. Poulter, J.G. Canadell, G. Hugelius, R.B. Jackson, A. Jain, M. Jones, M. Kondo, I.T. Luijkx, P.K. Patra, W. Peters, J. Pongratz, A.M.R. Petrescu, S. Piao, C. Qiu, C. Von Randow, P. Regnier, M. Saunois, R. Scholes, A. Shvidenko, H. Tian, H. Yang, X. Wang, and B. Zheng, 2022: Definitions and methods to estimate regional land carbon fluxes for the second phase of the REgional Carbon Cycle Assessment and Processes Project (RECCAP-2). *Geoscientific Model Development*, **15** (3), 1289–1316. https://doi.org/10.5194/gmd-15-1289-2022

264. USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/nca4.2018

265. Lisonbee, J., M. Woloszyn, and M. Skumanich, 2021: Making sense of flash drought: Definitions, indicators, and where we go from here. *Journal of Applied and Service Climatology*, **2021** (001), 1–19. https://doi.org/10.46275/joasc.2021.02.001

266. Swann, A.L.S., F.M. Hoffman, C.D. Koven, and J.T. Randerson, 2016: Plant responses to increasing $CO_2$ reduce estimates of climate impacts on drought severity. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (36), 10019–10024. https://doi.org/10.1073/pnas.1604581113

267. Eyring, V., N.P. Gillett, K.M.A. Rao, R. Barimalala, M.B. Parrillo, N. Bellouin, C. Cassou, P.J. Durack, Y. Kosaka, S. McGregor, S. Min, O. Morgenstern, and Y. Sun, 2021: Ch. 3. Human influence on the climate system. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 423–552. https://doi.org/10.1017/9781009157896.005

268. NCEI, n.d.: U.S. Climate Extremes Index (CEI). National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information, accessed April 7, 2023. https://www.ncei.noaa.gov/access/monitoring/cei/

269. Cook, B.I., J.S. Mankin, K. Marvel, A.P. Williams, J.E. Smerdon, and K.J. Anchukaitis, 2020: Twenty-first century drought projections in the CMIP6 forcing scenarios. *Earth's Future*, **8** (6), e2019EF001461. https://doi.org/10.1029/2019ef001461

270. Riahi, K., D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J.C. Cuaresma, S. Kc, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J.C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, and M. Tavoni, 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

271. Hausfather, Z., K. Marvel, G.A. Schmidt, J.W. Nielsen-Gammon, and M. Zelinka, 2022: Climate simulations: Recognize the 'hot model' problem. *Nature*, **605** (7908), 26–29. https://doi.org/10.1038/d41586-022-01192-2

272. Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi, 2014: Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, **2** (8), 383–406. https://doi.org/10.1002/2014ef000239

273. Levermann, A., P.U. Clark, B. Marzeion, G.A. Milne, D. Pollard, V. Radic, and A. Robinson, 2013: The multimillennial sea-level commitment of global warming. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (34), 13745–13750. https://doi.org/10.1073/pnas.1219414110

274. Goelzer, H., S. Nowicki, A. Payne, E. Larour, H. Seroussi, W.H. Lipscomb, J. Gregory, A. Abe-Ouchi, A. Shepherd, E. Simon, C. Agosta, P. Alexander, A. Aschwanden, A. Barthel, R. Calov, C. Chambers, Y. Choi, J. Cuzzone, C. Dumas, T. Edwards, D. Felikson, X. Fettweis, N.R. Golledge, R. Greve, A. Humbert, P. Huybrechts, S. Le clec'h, V. Lee, G. Leguy, C. Little, D.P. Lowry, M. Morlighem, I. Nias, A. Quiquet, M. Rückamp, N.J. Schlegel, D.A. Slater, R.S. Smith, F. Straneo, L. Tarasov, R. van de Wal, and M. van den Broeke, 2020: The future sea-level contribution of the Greenland ice sheet: A multi-model ensemble study of ISMIP6. *The Cryosphere*, **14** (9), 3071–3096. https://doi.org/10.5194/tc-14-3071-2020

275. Seroussi, H., S. Nowicki, A.J. Payne, H. Goelzer, W.H. Lipscomb, A. Abe-Ouchi, C. Agosta, T. Albrecht, X. Asay-Davis, A. Barthel, R. Calov, R. Cullather, C. Dumas, B.K. Galton-Fenzi, R. Gladstone, N.R. Golledge, J.M. Gregory, R. Greve, T. Hattermann, M.J. Hoffman, A. Humbert, P. Huybrechts, N.C. Jourdain, T. Kleiner, E. Larour, G.R. Leguy, D.P. Lowry, C.M. Little, M. Morlighem, F. Pattyn, T. Pelle, S.F. Price, A. Quiquet, R. Reese, N.J. Schlegel, A. Shepherd, E. Simon, R.S. Smith, F. Straneo, S. Sun, L.D. Trusel, J. Van Breedam, R.S.W. van de Wal, R. Winkelmann, C. Zhao, T. Zhang, and T. Zwinger, 2020: ISMIP6 Antarctica: A multi-model ensemble of the Antarctic ice sheet evolution over the 21st century. *The Cryosphere*, **14** (9), 3033–3070. https://doi.org/10.5194/tc-14-3033-2020

276. Eyring, V., S. Bony, G.A. Meehl, C.A. Senior, B. Stevens, R.J. Stouffer, and K.E. Taylor, 2016: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, **9** (5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

277. Archer, D. and R. Pierrehumbert, Eds., 2011: *The Warming Papers: The Scientific Foundation for the Climate Change Forecast*. Wiley-Blackwell, 432 pp. https://www.wiley.com/en-us/the+warming+papers%3a+the+scientific+foundation+for+the+climate+change+forecast-p-9781405196161

278. Matthews, H.D. and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, **35** (4). https://doi.org/10.1029/2007GL032388

279. Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the United States of America*, **106** (6), 1704–1709. https://doi.org/10.1073/pnas.0812721106

280. Matthews, H.D. and A.J. Weaver, 2010: Committed climate warming. *Nature Geoscience*, **3** (3), 142–143. https://doi.org/10.1038/ngeo813

281. Friedlingstein, P., 2015: Carbon cycle feedbacks and future climate change. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **373** (2054), 20140421. https://doi.org/10.1098/rsta.2014.0421

282. Lehner, F., C. Deser, N. Maher, J. Marotzke, E.M. Fischer, L. Brunner, R. Knutti, and E. Hawkins, 2020: Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. *Earth System Dynamics*, **11** (2), 491–508. https://doi.org/10.5194/esd-11-491-2020

Fifth National Climate Assessment: Chapter 3

# Earth Systems Processes

# Chapter 3. Earth Systems Processes

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# Introduction

The Earth system consists of the atmosphere, land, oceans, and cryosphere, which interact and cycle energy, water, and essential elements of life such as carbon, nitrogen, and phosphorus. Powered by the sun, these interactions and cycles determine Earth's climate, which naturally varies at a broad range of timescales from days to millennia through diverse Earth system processes.

Since industrialization, human activities have dramatically altered atmospheric composition and land cover, with consequential impacts on climate. Human-caused emissions of greenhouse gases have warmed the planet by trapping more outgoing energy, leading to a change in the net energy balance at the top of the atmosphere. The net increase in energy input warms the surface and the air and increases moisture in the lower atmosphere, resulting in significant changes in Earth system processes, including changes in atmospheric and oceanic circulations, clouds, and precipitation and melting of sea ice, glaciers, and ice sheets. The increase in energy input also provides fuel for increasing the frequency and intensity of extreme weather events such as heatwaves and convective storms.

In recent years, advances have been made in understanding the changes that have already occurred, attributing changes to human influence, and projecting future changes. These advances are facilitated by new and diverse observations, improved models and experiments, and the combination of observations and models to support multiple lines of evidence and inquiry. Building on previous scientific assessments, these advances have enabled scientists to unequivocally attribute the observed global warming to human activities and to narrow by 50% the range of estimated global warming that would be caused by a doubling of atmospheric carbon dioxide concentration. Complementary to Chapter 2, which focuses on past and future climate trends, particularly in the US, this chapter discusses more generally how Earth system processes respond to the drivers of climate change. It begins by introducing the natural and human (anthropogenic) drivers of climate change (KM 3.1). Next, it addresses our understanding of the climate response to those drivers, including the sensitivity of the climate to changing greenhouse gas concentrations and the feedback processes that can amplify or partially counteract the influences of human activities (KM 3.2). Recent advances in observations, modeling, and attribution of climate change are then discussed (KM 3.3). Lastly, changes in Earth system processes that underpin the many facets of global and regional climate change (KM 3.4) and changes in extreme events (KM 3.5) are discussed.

## Key Message 3.1

## Human Activities Have Caused the Observed Global Warming

Human activities—primarily emissions of greenhouse gases from fossil fuel use—have unequivocally caused the global warming observed over the industrial era. Changes in natural climate drivers had globally small and regionally variable long-term effects over that period.

Shifts in climate at the global scale occur primarily in response to processes that change the balance between incoming solar energy and the outgoing energy radiated from Earth at the top of the atmosphere (TOA). The drivers of change are both natural and human-caused and may be transient or long-lived. Changes in TOA net radiation balance resulting from a perturbation in climate drivers can be quantified in terms of the effective radiative forcing (ERF), measured in units of watts per square meter ($W/m^2$). The main natural drivers of climate change—variations in solar radiation and volcanic aerosols—have negligible contributions to long-term climate forcing.[1,2] Warming from fossil fuel emissions of carbon dioxide ($CO_2$) is expected to last centuries to millennia, because of the slow rate of the natural processes that remove $CO_2$

from the atmosphere. Changes in climate may be further amplified or diminished through feedbacks in the climate system. Feedbacks are processes changed by the warming that then modify the TOA radiation balance and the overall level of warming. In the surface–albedo feedback, for example, warming melts ice cover over the land and ocean, exposing darker surfaces beneath that absorb more energy rather than reflecting it, contributing to further warming. See Chapter 2 of the Climate Science Special Report[3] for further details on emissions sources, radiative forcing, and ERF.

## *Anthropogenic Drivers*

### Well-Mixed Greenhouse Gases

Since the release of the Fourth National Climate Assessment (NCA4) in 2018, global atmospheric abundances of the main well-mixed greenhouse gases (WMGHGs), including $CO_2$, methane ($CH_4$), and nitrous oxide ($N_2O$), have continued to increase (KM 2.1). Atmospheric abundances of halogenated gases have also changed, some increasing and some decreasing due to ozone-depletion policies. Preindustrial to present-day (1750–2019) increases in WMGHG concentrations contributed the bulk of the total human-caused forcing, with increases in $CO_2$ contributing an ERF of 2.16 ± 0.26 W/m$^2$, followed by 0.54 ± 0.11 W/m$^2$ from $CH_4$, 0.41 ± 0.08 W/m$^2$ from halogenated compounds, and 0.21 ± 0.03 W/m$^2$ from $N_2O$.[2] The ERF due to changes in $CH_4$ abundance is lower than that due to changes in emissions because of offsetting effects of other chemical constituents as discussed below.

The growth in global atmospheric $CO_2$ levels since 1750 was primarily driven by direct emissions from human activities such as fossil fuel combustion, cement manufacturing, and land-use change. About 41% ± 11% of the 700 ± 75 PgC of $CO_2$ (1PgC = 1 billion metric tons of carbon [GtC]) emissions between 1750 and 2019 remain in the atmosphere today, with the rest absorbed by oceans and the land biosphere.[4]

Methane is considered both a WMGHG and a short-lived climate forcer due to its chemical reactivity and an approximate 10-year atmospheric lifetime. Methane is produced by both natural processes and human activities. Observational evidence points to microbial sources (agriculture, waste, and natural wetlands) as the predominant cause of the observed increase in global growth in atmospheric $CH_4$ since 2006,[5,6] with a smaller contribution from fossil fuel production.

In addition to its direct effect on radiative forcing, $CH_4$ also has an indirect influence through its chemical effects on other climate drivers, including $CO_2$, ozone, stratospheric water vapor, aerosols, and halogenated gases.[7] This leads to an increased effect of $CH_4$ on the amount of energy trapped in the Earth system. Over 20 and 100 years, a given mass of $CH_4$ emissions is about 80 and 30 times, respectively, more efficient at trapping energy in the climate system than the same emitted mass of $CO_2$.[2] This comparison of energy trapped due to a given mass of emitted gas compared to the same emitted mass of $CO_2$ is known as the global warming potential (GWP), and it is always specified for a given time horizon due to the varying chemical lifetimes of non-$CO_2$ greenhouse gases. For $CH_4$, the 100-year GWP is about 30 (relative to a GWP for $CO_2$ being, by definition, equal to 1 over the same 100-year period).

The increase in atmospheric $N_2O$ levels since 1750 is small compared to that of $CO_2$ and $CH_4$, although rates have increased in recent years due to increased nitrogen fertilizer use in agriculture.[8] Nitrous oxide has an atmospheric lifetime of about 116 years and is nearly 300 times more efficient at trapping energy than $CO_2$ over a 100-year period.[9]

Many halogenated compounds, which are primarily manufactured gases, also contribute to climate change. These include chlorofluorocarbons (CFCs), perfluorocarbons (PFCs), and sulfur hexafluoride ($SF_6$), with lifetimes of decades to millennia, and hydrogen-containing halogenated compounds like hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), with lifetimes of months to decades. The atmospheric abundances of most CFCs have continued to decline in response to regulations under the Montreal

Protocol on Substances that Deplete the Ozone Layer and its amendments.[10] Atmospheric levels of HFCs are increasing, while the rates of atmospheric growth of major HCFCs have slowed down in recent years.

## Non-methane Short-Lived Climate Forcers

Short-lived climate forcers (SLCFs) are chemically reactive in the troposphere (lower atmosphere), with atmospheric lifetimes typically shorter than two decades, and include ozone, aerosols, and methane. Most SLCFs are also air pollutants or precursors for air pollution (see KM 14.5). An assessment of the ERF effects for two primary non-methane SLCFs are given below.

**Ozone**: Ozone is a greenhouse gas that occurs naturally throughout the atmosphere and is a harmful air pollutant near the surface (KM 14.1). It is formed in the atmosphere through chemical reactions involving sunlight: in the stratosphere, ozone production occurs via chemical reactions involving the breakdown of oxygen molecules by sunlight, while in the troposphere, it is produced by chemical reactions involving emissions of methane, nitrogen oxides (nitric oxide and nitrogen dioxide), carbon monoxide, and non-methane volatile organic compounds in the presence of sunlight. Increases in human-caused emissions of these precursors since preindustrial times are responsible for increases in tropospheric ozone.[7,11] In the stratosphere, increases in human-caused halogenated ozone-depleting substances (ODSs) have contributed to declining ozone abundances. Over the period 2000–2017, stratospheric ozone concentrations have increased slightly in response to declining ODSs because of the Montreal Protocol and its amendments.[10] The combined changes in tropospheric and stratospheric ozone from the preindustrial era to the present have had an overall warming effect of 0.47 ± 0.23 $W/m^2$, with a smaller contribution from stratospheric ozone changes.[2]

**Aerosols**: Aerosols are small particles that are emitted directly from human activities and natural processes and are also formed in the atmosphere via reactions involving gaseous precursor emissions. Ice core records indicate that aerosol concentrations increased from the preindustrial era until the 1970s and 1980s, driven by northern midlatitude emissions, and declined thereafter.[10] This decline is attributed to reductions in emissions from Europe and North America due to air quality regulations. Satellite data and ground-based records over the modern period confirm the decline in aerosol concentrations over the northern midlatitude and Southern Hemisphere continents but show increases over South Asia and East Africa.[10,12] Globally, aerosol concentrations have been declining since 2000, driven by reductions in some regions. Aerosols from human activities are also air pollutants (KMs 14.1, 2.1) and influence Earth's radiation balance directly by scattering or absorbing solar radiation, through interactions between aerosols and clouds, and by changing the surface reflectivity when light-absorbing aerosols are deposited on snow and ice. Changes in aerosols over the period 1750–2014 have had an overall cooling effect of –1.3 ± 0.7 $W/m^2$.[2] Since NCA4, the uncertainty in total aerosol ERF has been reduced, and it is now *virtually certain* that the total aerosol ERF is negative, as discussed in the Technical Summary of the Working Group I contribution to the Intergovernmental Panel on Climate Change Sixth Assessment Report.[13]

## Land-Use Effects on Surface Albedo

Anthropogenic water storage, agricultural practices, and forest cover changes modify the land surface and alter the surface energy balance. Increased water storage on land reduces surface reflectivity and has a localized cooling effect due to evaporation. Irrigation of crops has a similar localized cooling effect through both increased evaporation and plant transpiration.[14] Forests can induce warming because they absorb surface energy or induce cooling because of transpiration.[15] Deforestation can cause cooling by brightening the surface and increasing ground evaporation, but it may also cause warming by reducing ground shading and plant transpiration.[16] Overall, global changes in land use have contributed a net negative ERF (cooling effect) of –0.20 ± 0.10 $W/m^2$.[2]

## Natural Drivers

### Solar Irradiance

Climate forcing from changes in solar irradiance are small relative to changes in anthropogenic greenhouse gases over the industrial era. Changes in solar irradiance over the period 1750–2019 have contributed an ERF of 0.01± 0.07 W $m^{-2}$.[2]

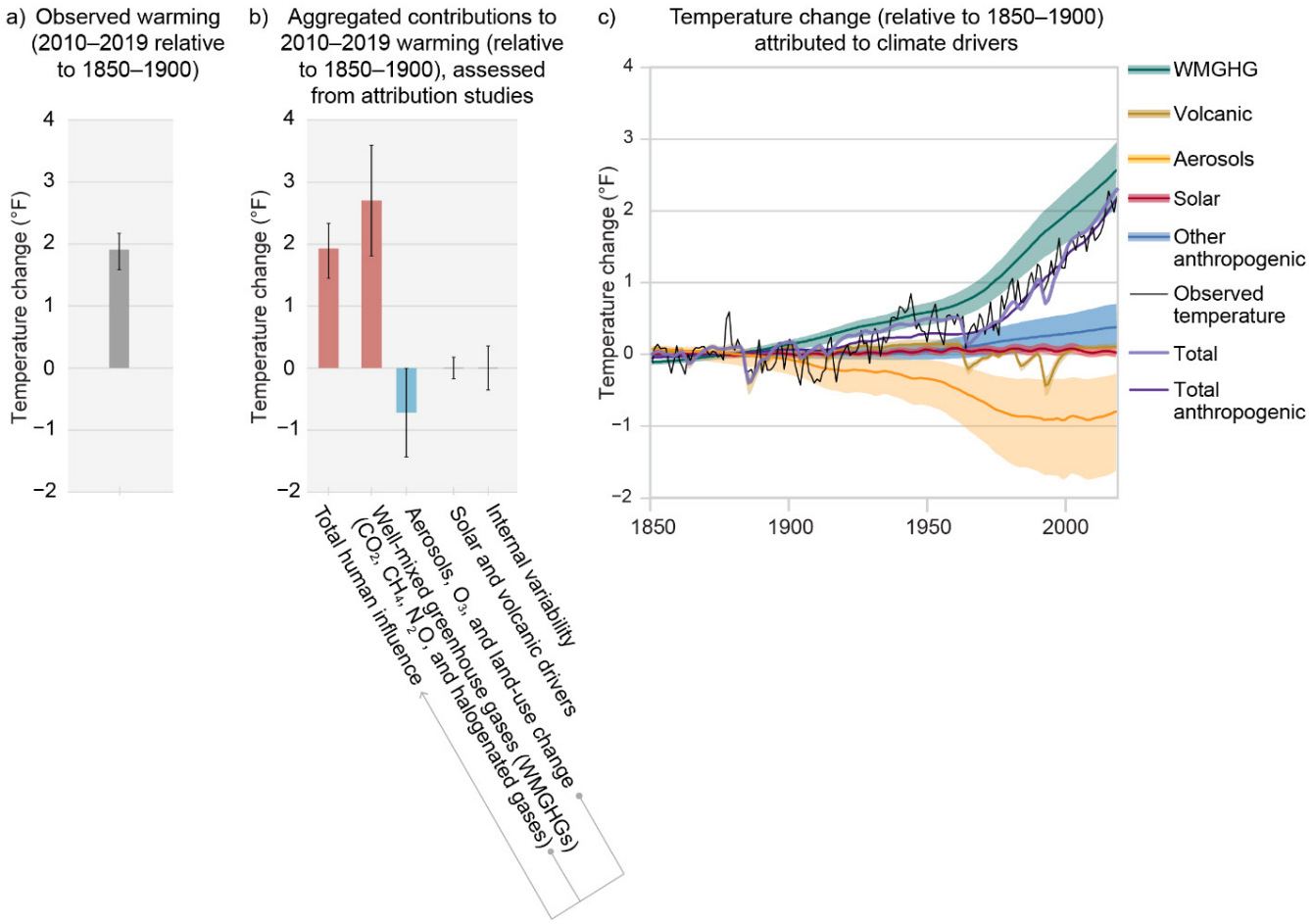
### Volcanic Aerosols

Sulfate aerosols formed in the stratosphere from injections of sulfur dioxide ($SO_2$) from explosive, episodic volcanic eruptions and more frequent smaller eruptions reduce incoming solar radiation and lead to a cooling effect. Volcanic aerosols can also trigger changes in upper-tropospheric clouds, leading to warming,[17,18] although the magnitude of this effect is highly uncertain.[19] Quantitative assessment of the net ERF over the industrial era for volcanic aerosols shows negligible effects on the long-term temperature trends.

## Global Surface Temperature Response to Climate Drivers

A notable recent advance is the quantification of the contributions to global surface air temperature change over the preindustrial to present-day period due to forcings from changes in different climate drivers.[2] Panels a and b in Figure 3.1 show that observed warming in 2010–2019 (compared to 1850–1900) is dominated by contributions from WMGHGs and ozone. This warming has been partially counteracted by the cooling effect from aerosols and land-use change. Because of declining aerosols, the global aerosol cooling effect has weakened since about 1980, and the rate of global warming has increased, mainly due to increasing greenhouse gases (Figure 3.1c). The aerosol cooling effect has a strong regional dependence,[7] contributing to differences in regional climate change (KM 3.4). Natural drivers over the historical period have contributed a small, highly variable cooling effect. Uncertainties in the ERF values, especially of aerosols, contribute to uncertainty in the attribution of observed warming.

## Observed Global Warming and Attribution to Climate Drivers




**The warming observed over the industrial era was driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling.**

**Figure 3.1.** The figure shows (**a**) observed change in global average surface temperature in 2010–2019 relative to 1850–1900; (**b**) temperature change over the same period (also relative to 1850–1900) attributed to total human influence, including changes in well-mixed greenhouse gas concentrations (including carbon dioxide [$CO_2$], methane [$CH_4$], nitrous oxide [$N_2O$], and halogenated gases); combined changes in aerosols, ozone ($O_3$), and land use (land-use reflectance); and solar and volcanic drivers and natural climate variability; and (**c**) time evolution of observed temperature (2010–2019, relative to 1850–1900; black line) attributed to different climate drivers from 1850 to 2019, as well as total human influence ("Total anthropogenic"; purple line) and combined natural and human influence ("Total"; lavender line). Whiskers in (a) and (b) show the *very likely* range, while shaded uncertainty bands in (c) show *very likely* (5%–95%) ranges. Note that in (b), the warming effect of ozone is largely offset by the cooling effect of aerosols, resulting in a net cooling when the effects of aerosols, ozone, and land-use change are combined. (a, b) Adapted with permission from Figure SPM.2 in IPCC 2021;[20] (c) adapted with permission from Figure 7.8 in Forster et al. 2021[2] and Figure 2.11c in Gulev et al. 2021.[10]

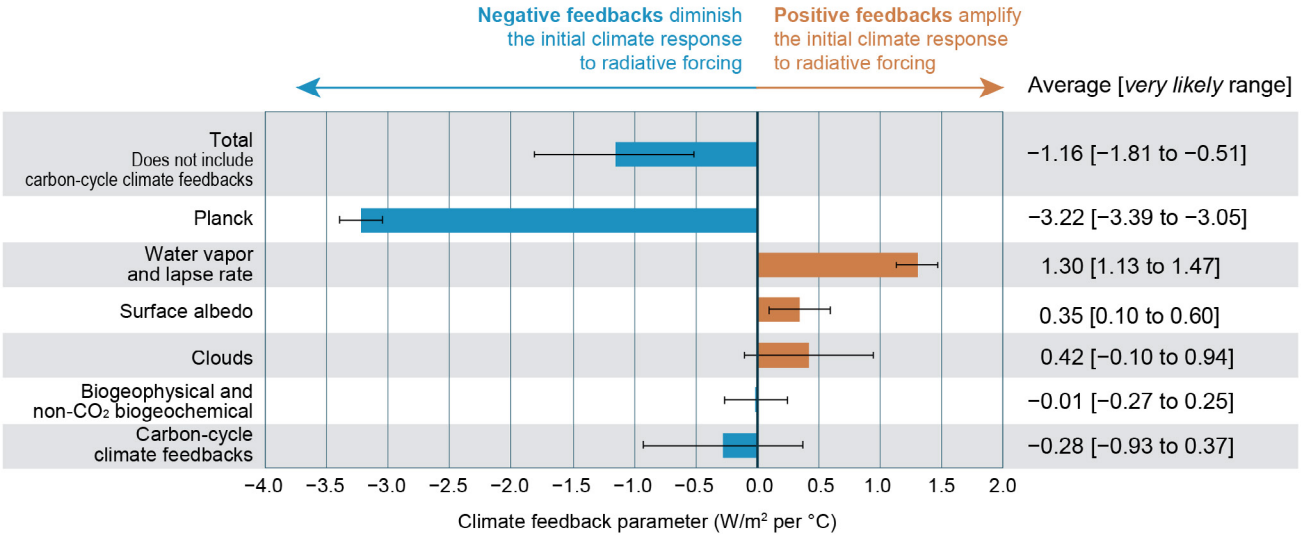
## Key Message 3.2

# The Estimated Range of Climate Sensitivity Has Narrowed by 50%

Recent improvements in the understanding of how climate feedbacks vary across timescales have narrowed the estimated *likely* range of warming expected from a doubling of atmospheric carbon dioxide by 50% to between 4.5°F and 7.2°F (*high confidence*).

The total climate response for a given forcing is an important indicator of the expected climate change impacts. This response is commonly characterized by the equilibrium climate sensitivity (ECS), defined as the change in global average surface temperature after the climate system reaches a steady state following a doubling of the atmospheric $CO_2$ concentration. A larger value of ECS indicates larger increases in global warming for a given increase in greenhouse gases. ECS depends both on the ERF from a doubling of $CO_2$ and the sum of climate feedbacks that can either amplify (a positive feedback) or dampen (a negative feedback) the temperature change. The primary feedbacks arise from increased emissions of longwave radiation that cools the warmer planet (Planck feedback); increases in atmospheric water vapor (a greenhouse gas); changes in the vertical profile of atmospheric temperature; reductions in the surface area covered by reflective snow and ice; and changes in cloudiness. Cloud feedbacks are the largest source of ECS uncertainty (Figure 3.2).[2,21] The response of the carbon cycle to climate warming contributes additional uncertainty (KM 3.4).

## Feedbacks in the Climate System

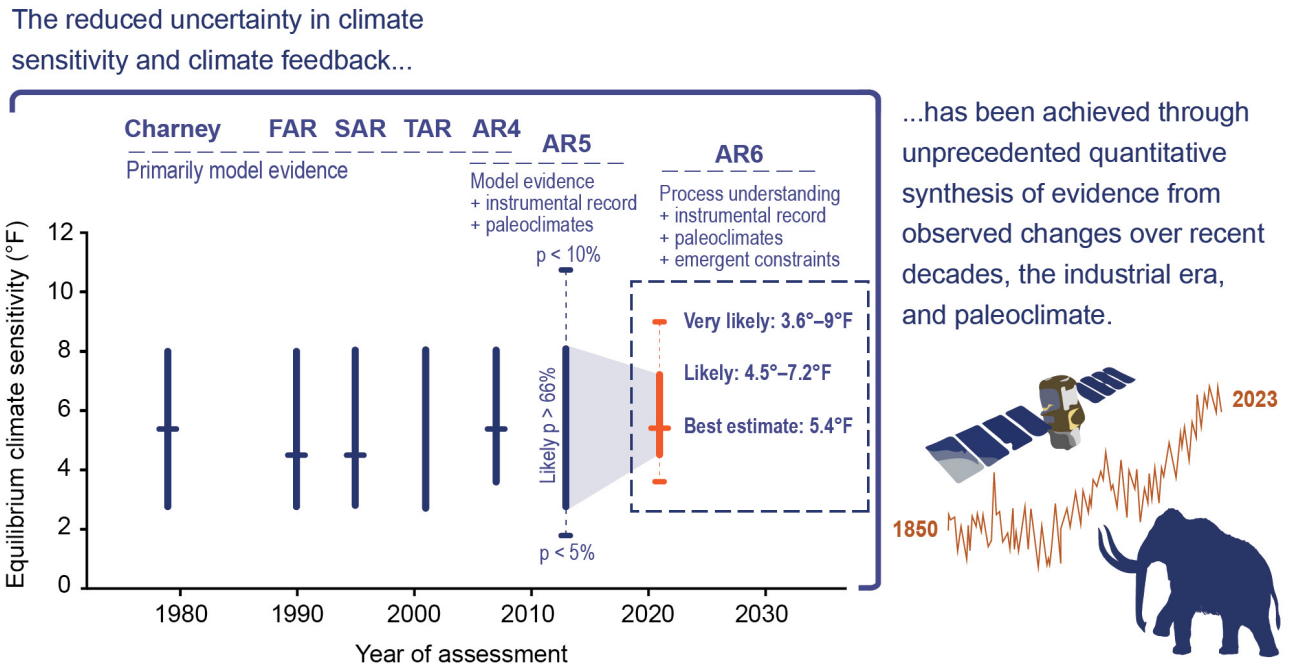



**Multiple feedback processes in the climate system amplify or partially diminish the response to radiative forcing; quantifying their values is necessary to determine the climate response to human activities.**

**Figure 3.2.** The graph shows assessed values of feedbacks acting in the climate system. The total feedback is the feedback that contributes to the assessed value of climate sensitivity. Bars denote the average feedback values, and uncertainties denoted by whiskers represent *very likely* ranges. Negative feedbacks are denoted by blue bars and positive feedbacks by orange bars. The feedback values are estimated by climate models based on the equilibrium change in Earth's energy balance in response to a doubling of carbon dioxide ($CO_2$) with and without the feedback processes. $W/m^2$ is watts per square meter. Adapted with permission from Figure TS.17 in Arias et al. 2021.[13]

The key development since NCA4 is that the ECS uncertainty range has narrowed.[2,21] Recent assessments place ECS between 4.5°F and 7.2°F (2.5°C and 4.0°C), a 50% uncertainty reduction from previous assessments (Figure 3.3). It is *virtually certain* that ECS is greater than 2.7°F (1.5°C), guaranteeing significant climate change impacts from ongoing increases in $CO_2$ and other greenhouse gases.

## Advances in Understanding Climate Sensitivity and Climate Feedback




**Uncertainties in climate sensitivity and feedbacks have been reduced by synthesizing multiple lines of evidence.**

**Figure 3.3.** The graph (**left**) shows estimates of equilibrium climate sensitivity (ECS; y-axis) and the considered lines of evidence as a function of the years (x-axis) in which various assessment reports were released. These assessments include the "Charney Report"—a study by an ad hoc US research group that was published in 1979—and the first through sixth assessment reports produced by the Intergovernmental Panel on Climate Change (IPCC), indicated here by the acronyms FAR, SAR, TAR, AR4, AR5, and AR6, respectively. NCA adopts the climate sensitivity values assessed by IPCC reports. Thick vertical bars indicate the *likely* range, and the horizontal tick marks on these bars, where present, indicate the best estimate (tick marks for the AR5 indicate a less than 5% probability of ECS being below 1.8°F and less than 10% probability of being greater than 10.8°F). The reduced estimated range of ECS in AR6 reflects advances in understanding of how climate feedbacks operate across timescales and an improved ability to combine physical constraints with observational data from recent decades, the industrial era, and paleoclimate records. The images of a satellite, the surface temperature time series, and a woolly mammoth (**right**) are emblematic of these three lines of evidence used to assess climate sensitivity. Adapted with permission from Figure TS.16a in Arias et al. 2021.[13]

This uncertainty reduction results from advances in combining observations and targeted modeling results from nearly independent lines of evidence, each of which generally agrees on the values of ECS. The lines of evidence include 1) observed present-day variations on monthly to interannual timescales from which cloud and other climate feedbacks are inferred; 2) observed temperature changes between the preindustrial period and present and associated relationships to ERF; and 3) estimated temperature and radiative forcing changes for multiple warm and cold periods in paleoclimate records.[21]

Advances since NCA4 include the following:

- Increased use of present-day observations to determine cloud and other climate feedbacks. Confidence in inferring feedbacks for centennial-scale climate changes from present-day variations on monthly to interannual timescales is bolstered by "emergent constraints" found in Coupled Model Intercomparison Project (CMIP) model ensembles (see App. 3).
- Increased use of very-high-resolution cloud-resolving models to determine expected changes in response to the warmer conditions
- Greater understanding of how changes in the spatial distribution of sea surface temperature over the historical period affected climate feedbacks
- Greater availability of reconstructed temperatures and ERF values for paleoclimate and greater confidence in how to account for the state-dependence of climate feedbacks and departures from equilibrium

The reduction of uncertainty in ECS was accompanied by reduced uncertainty in the cloud feedback. There is greater confidence that the sum of feedbacks over all cloud types is positive (i.e., a warming effect) and primarily results from increases in the altitude of high-level clouds and decreases in the amount of marine stratocumulus and continental low-level clouds. A previously identified negative feedback arising from the transition of cloud phase from ice to liquid as the planet warms[22] is now thought to be substantially smaller based on new observational evidence.[23,24]

Importantly, the new assessed range of ECS relies on observational analyses and selected modeling evidence but does not consider the ECS values from climate models directly. Models with ECS values outside of the assessed range are thought to have *unlikely* values of ECS. In particular, the CMIP6 models with ECS values greater than 9°F (5°C) may simulate an unrealistically early timing of reaching a given global warming level (GWL). Despite their unrealistic timings, these models may still be used to estimate the climate impacts occurring at a given GWL.[25]

## Key Message 3.3

## New Data and Analysis Methods Have Advanced Climate Science

A number of scientific developments have enabled deeper understanding of climate processes and their responses to human influence. Observational records have lengthened, and new observing systems have come online. New scenarios of socioeconomic development, and their associated emissions and land-use changes, drive updated climate projections from Earth system models. Large ensemble simulations from multiple models have enabled scientists to better distinguish anthropogenic climate change from natural climate variability. More targeted model evaluation techniques are using observations to narrow the estimated range of future climatic changes. Finally, advances in methods for extreme event attribution enabled scientists to estimate the contributions of human influence to some types of individual extreme events in near-real-time.

### *Advances in Earth System Observations*

Surface and satellite observational products continue to provide deep insights into recent changes in the Earth system. New analyses based on long-term surface observations provide improved constraints on regional plant productivity and the moderating influences of water and nutrients (e.g., AmeriFlux sites and National Ecological Observatory Network [NEON] domains), on surface and subsurface runoff (e.g., USGS observing networks), on surface energy balance (e.g., Atmospheric Radiation Measurement [ARM] and other Baseline Surface Radiation Network [BSRN] sites), on uncertainty in near-surface temperatures (e.g., Goddard Institute for Space Studies Surface Temperature [GISTEMP]), and on atmospheric $CO_2$ and related gases (e.g., NOAA Earth System Research Laboratories Global Monitoring Laboratory [NOAA ESRL GML]). In situ measurements of ocean temperature, salinity, and key biogeochemical concentrations are provided by buoys, ship tracks, floats and drifters (NOAA Global Drifter Program [GDP]), and Saildrones. Extended records from the Clouds and the Earth's Radiant Energy System (CERES) and Atmospheric Infrared Sounder (AIRS) satellite missions now provide increasing confidence in warming of the Earth's atmosphere and surface. Continued analysis of the now 30-year record of sea level heights from a series of satellite altimeters provides observations of a recent acceleration in sea level rise. However, continuing declines in the number of active in situ precipitation monitoring stations threaten to produce gaps in our precipitation observation record.[26]

Recently deployed observing systems promise a deeper understanding of Earth's physical systems and reduced uncertainty in climate projections. Recent NASA missions include the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) thermal imager, focused on vegetation temperature and response to climate stressors; the Global Ecosystem Dynamics Investigation (GEDI) ecosystem lidar, focused on the forest canopy; the Earth Surface Mineral Dust Source Investigation (EMIT) spectrometer; and the Surface Water and Ocean Topography (SWOT) mission in conjunction with the Centre National d'Études Spatiales, the Canadian Space Agency, and the United Kingdom Space Agency, focused on measuring surface water on land and ocean sea surface height. Other recently launched or forthcoming missions include NASA's Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) and NOAA's Joint Polar Satellite System-2 (JPSS-2), focused on tropical cyclones and other extreme weather events. Additional frontiers in satellite-based climate monitoring include both hydrological (e.g., snow thickness) and atmospheric (e.g., clouds and atmospheric composition) properties. Besides satellite observations, NASA Jet Propulsion Laboratory's Airborne Snow Observatory (ASO) and its commercial successor have performed numerous snow surveys, enabling extremely detailed

maps of mountain snowpack. Also, recent efforts by USGS on the Next Generation Water Observing System (NGWOS) are enhancing the quality of real-time data on water quantity and quality from fixed and mobile instruments.

Combined with newer algorithms and data assimilation techniques, a growing number of observational data products enable tighter constraints for modern reanalysis datasets, such as Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA2) and the European Centre for Medium-Range Weather Forecasts Reanalysis, Version 5 (ERA5). Improvements in the number and quality of observational data products have also enabled new process-oriented metrics and diagnostics (e.g., Leung et al. 2022;[27] Maloney et al. 2019;[28] Simpson et al. 2020[29]), which in turn enhance the validation of Earth system models (ESMs).

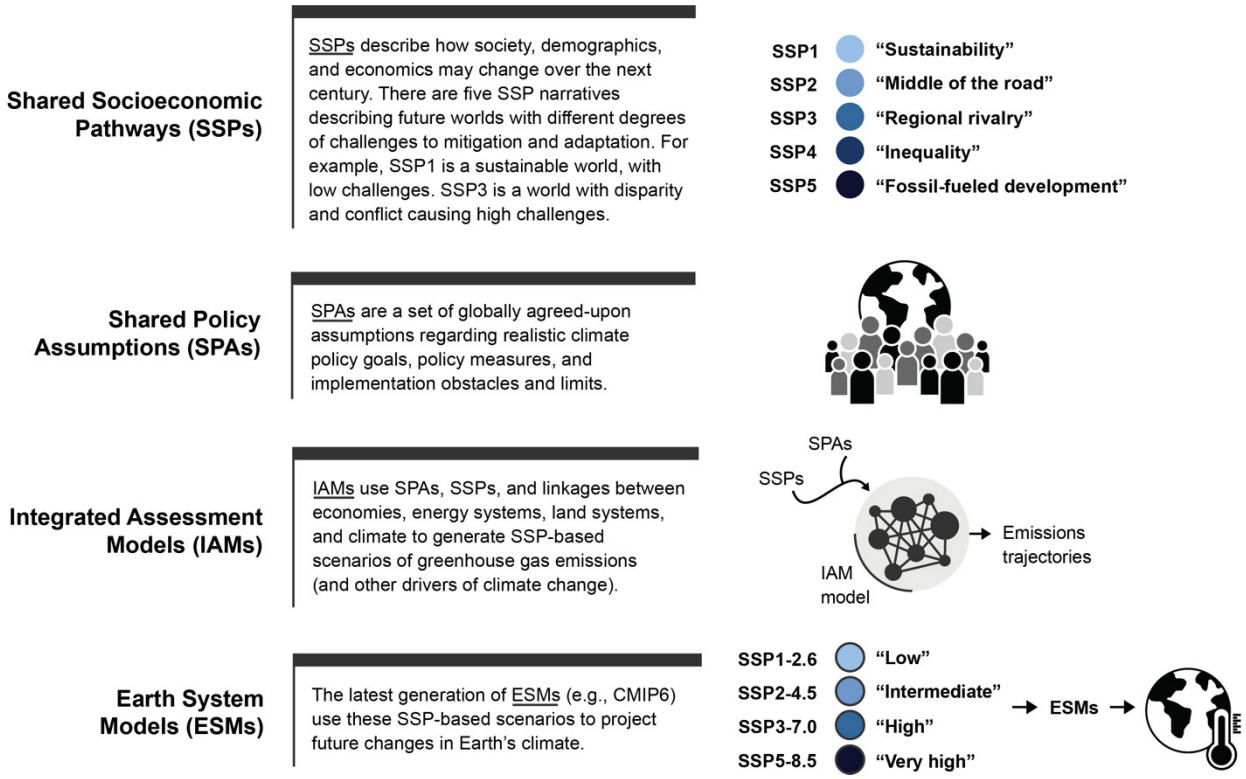
## *New Scenarios and Climate Projections*

A new generation of ESMs has produced an updated set of projections under many new policy-relevant scenarios. A number of ESMs have been run at significantly higher resolution (about 20–50 km) than the previous standard (about 100–200 km) for focused experiments to explore particular aspects of climatic changes, like tropical cyclones, that cannot be simulated by coarser-resolution models.

The Scenario Model Intercomparison Project (ScenarioMIP)[30] organized the main set of 21st-century projection experiments under the latest phase of the Coupled Model Intercomparison Project, CMIP6. These CMIP6 projections used newly developed scenarios based on Shared Socioeconomic Pathways (SSPs; Figure 3.4).[31,32,33] Five SSPs represent alternative plausible trajectories of 21st-century GDP and population growth and the pace and pervasiveness of socioeconomic and technological progress within individual nations and across the world (see Table 3 in the Guide to the Report). SSP-specific drivers are used in integrated assessment models (IAMs) to simulate the corresponding evolution of the energy system and the resulting greenhouse gas trajectories. These are in turn used by ESMs to drive their 21st-century projections. Some of these trajectories are also modified by imposing mitigation policies that meet specific warming targets (e.g., 1.5°C [2.7°F] or 2°C [3.6°F] above preindustrial levels) by the end of the century.[34] Figure 3.4 describes this process step-by-step.

Note that the mitigation assumptions in the various scenarios are not directly relatable to the mitigation discussion in Chapter 32, where the analysis is specifically centered on the current mitigation targets of the US in view of the Paris goals. The stringent goals of net-zero $CO_2$ emissions by 2050 that Chapter 32 discusses for the US are, however, consistent with the lowest scenario adopted in ScenarioMIP.

## SSP-Based Scenarios and Their Use in Climate Model Projections




**Projections of future climate involve a multistep process using scenarios about future socioeconomic developments, policy goals, and emissions to drive Earth system models.**

**Figure 3.4.** The graphic shows the chain of development leading to Earth system model experiments under CMIP6 ScenarioMIP, the most up-to-date 21st-century climate change projections. Five societal development pathways (the SSPs) were produced. Then, assumptions about climate mitigation policies that could be consistently applied to those socioeconomic futures were developed (the SPAs). Integrated assessment models took these baseline or mitigated pathways and produced alternative plausible trajectories of greenhouse gas emissions and land-use change. Earth system models used those emissions and land-use changes as inputs to produce the new CMIP6 scenarios of climate outcomes. Figure credit: Pacific Northwest National Laboratory, NOAA NCEI, and CISESS NC.

The new scenarios are labeled "SSPX-Y," where SSPX (with X ranging from 1 to 5) identifies the SSP used to produce the greenhouse gas trajectories and Y indicates the magnitude of the radiative forcing by 2100 in $W/m^2$. The main 21st-century trajectories from the CMIP6 ensemble are SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, along with SSP1-1.9, the lowest emissions trajectory, which is designed to stay below 1.5°C (2.7°F) of warming above preindustrial levels. These scenarios are intended to provide a representative set of plausible alternative pathways of greenhouse gas and aerosol emissions and land-use changes, according to alternative societal and economic development trends over the 21st century. Three new scenarios correspond to three of the Representative Concentration Pathway (RCP) scenarios used in CMIP5 in their overall forcing levels (SSP1-2.6 with RCP2.6, SSP2-4.5 with RCP4.5, and SSP5-8.5 with RCP8.5), albeit with different details in their composition of gases and land use. Scenario projections can be used to explore climate outcomes under a coherent future trajectory of greenhouse gases and other anthropogenic forcings.

An alternative perspective on the effects of climate change uses GWLs as an organizing principle. One can ask when a certain GWL will be reached for a given scenario and climate model, thus connecting the two perspectives. CMIP6 includes many experiments performed by many ESMs at about 100 km resolution.[35] A multimodel approach, the High Resolution Model Intercomparison Project (HighResMIP),[36] is featured for the first time in CMIP6 to systematically investigate the impact of horizontal resolution. Models par-

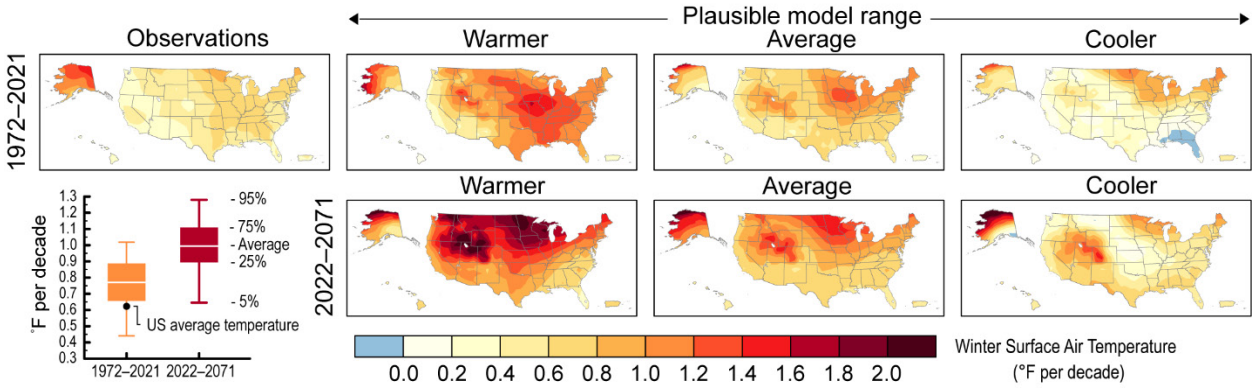
ticipating in HighResMIP have resolutions between 20 and 50 km and show more realistic simulations of intense storms and resulting precipitation.[37,38] At these resolutions, they can explicitly represent tropical cyclones,[39,40,41] and their simulations support the conclusion of a global decrease in tropical cyclone frequency[42] together with an increase in intensity with warming. Their more refined topography also enhances their representation of local processes, such as the effects of warming on mountain snowpack—an important water source for the western United States.[43]

Storyline simulations are another strategy to develop future projections.[44,45,46] In one variation of this approach, ensembles of short initialized weather hindcast simulations under imposed warming conditions can provide actionable information at regional or local scales.[47,48,49] Longer multiyear simulations can also be performed to understand changes in the statistics of weather extremes and storm characteristics (e.g., Chen et al. 2023;[50] Gutmann et al. 2018[51]) or to explore future change in climatic extremes such as drought (e.g., Ullrich et al. 2018[52]).

## *Large Ensemble Simulations*

Many realizations of the past and future climate are generated from climate model simulations started from initial conditions that are slightly perturbed from one another. These small random perturbations, the so-called butterfly effect, can subsequently alter the chaotic sequence of weather and climate events and, hence, the future course of the variability simulated by the model. Recently, climate model experiments have been conducted using multiple climate models with small random perturbations at the start of the simulations. The advent of these initial-condition large ensembles (henceforth referred to as large ensembles) in climate modeling provides an explicit framework for quantifying the relative contributions of external drivers and natural variability to regional climate change by sampling different possible sequences of natural variability that share a common forced response.[53] The application of large ensembles to assess the possible range of climate trends at local and regional scales is a major advance in recent years (Figure 3.5). New experiments from multiple climate models that capture uncertainty due to natural variability, changes in variability, and model uncertainty have improved our ability to understand and quantify expected climatic changes and the relative contributions of human-caused climate change and natural climate variability at regional scales. A new insight from the large ensemble archive is that different models have different representations of natural climate variability and how such variability responds to anthropogenic climate change. For some variables, such as precipitation, variability consistently increases with global warming, and large ensembles provide important context for quantifying and understanding these changes.

## Winter Surface Air Temperature Trends in Large Ensemble Simulations




**Large ensemble simulations provide a plausible range of trends in winter surface air temperature combining the human-caused climate change and natural variability. The observed trend falls within the range simulated by the large ensemble for the historical period.**

**Figure 3.5.** This figure shows past and projected future trends (in °F per decade) in winter (December–February) average air temperature over the United States and its territories (except the US-Affiliated Pacific Islands [USAPI]). The top row shows the observed trends during 1972–2021 (panel labeled "Observations") and the plausible model range of trends simulated by the CESM2 100-member Large Ensemble during 1972–2021 (panels labeled "Warmer," "Average," and "Cooler"). Here, "warmer" means the ensemble member with the 5th largest US-average trend, "cooler" means the ensemble member with the 5th smallest US-average trend, and "average" means the average trend across all 100 ensemble members. Note that the model range results from the combined influences of simulated natural variability and human-caused climate change. The bottom row of maps shows the plausible model range of trends simulated by the Community Earth System Model 2 (CESM2) 100-member Large Ensemble projected for 2022–2071 under the SSP3-7.0 radiative forcing scenario (panels labeled "Warmer," "Average," and "Cooler"; see above for definitions). White areas on the maps are major lakes, including Great Salt Lake, Lake Okeechobee, and Lake Tahoe. Trend values in the USAPI (not shown) are very similar to those for the Hawaiian Islands. The box plot at the lower left shows the distribution of US-average trends simulated by the CESM2 100-member Large Ensemble for the period 1972–2021 (orange) and projected for the period 2022–2071 (red). The thin white line within each box denotes the average value, and the boundaries of the box show the 25th–75th percentile range. The black dot shows the observed US-average trend during 1972–2021, which lies within the plausible model range of trends. Figure credit: National Center for Atmospheric Research.

## *Emergent Constraints on Future Projections*

An approach to reduce uncertainty in climate change projections has matured over the past decade. It is known as "emergent constraints."[54] The term refers to strong statistical relationships between highly uncertain future climate parameters and observable trends or variations in the current climate, along with a physical explanation of this relationship. Observations of the current climate are used to quantify the difference between simulated and observed values in a model simulation (referred to as model bias) and subsequently constrain the future climate parameters. Research on emergent constraints has targeted a wide variety of geophysical processes.[55] For example, projections of western US runoff in CMIP5 models can be constrained by the observed sensitivity of runoff to precipitation in the historical climate.[56] A linear relationship between the projected summer warming and the model warm bias over the central US in CMIP5 models can be used to correct the future temperature projections,[57] and the observed interhemispheric asymmetry of the intertropical convergence zone has been used to correct future projections of California winter precipitation.[58]

### *Extreme Event Attribution*

The science of evaluating the effects of human-caused climate change on extreme weather and climate events has advanced significantly. Human influence has changed the frequency and intensity of some types of extreme events, and it is now possible to quantify the influence of anthropogenic climate change on certain types of specific extreme events.

Extreme event attribution quantifies the current human influence on observed severe weather events, primarily through changes in magnitude and frequency.[59] Recent methodological advances have widened the classes of weather events analyzed and extended these analyses beyond single events to include hazards throughout an entire season (e.g., Herring et al. 2022,[60] 2019,[61] 2018;[62] Reed et al. 2022;[63] Wehner et al. 2019[64]). Confidence in attribution statements is increased when multiple methods, observations, and models lead to similar conclusions[65] and similar underlying trends are detected.[66]

Recent methodological advances include graphical methods to identify cause and effect pathways,[67] using physical insight to inform statistical models,[68,69] factual and counterfactual simulations,[70] and large ensembles.[71] The CMIP5/6 databases are often used in event attribution studies, but the relative coarseness of the model grids (100 km or more) limits applicability to large-scale events such as certain heatwaves[72] and winter storms.[73] Finer-scale events such as intense storms are often amenable to storyline hindcast simulations (see New Scenarios and Climate Projections above), using higher-resolution regional models to compare the "storm that was" with observed climate change to the "storm that might have been" without the human changes to the climate system.[74,75] However, by construction, such storyline analyses inform attribution statements about changes in the magnitude of an event not the frequency.

Attribution methods have advanced such that rapid statements can be made just weeks after an event[76,77] and even forecasted,[78] and these analyses could be made operational.[79] Despite recent progress, the human influence on some extreme weather events may not be attributable because of model limitations.[80,81]

Extreme event attribution has shown that some extreme events are happening with greater frequency, magnitude, and duration due to anthropogenic climate change. For example, climate change *very likely* made a 2016 extreme precipitation event in Louisiana heavier[77] and increased both precipitation[82,83,84] and flooding[85] during Hurricane Harvey. While these studies reveal how climate change affects extreme events, they also reveal that historical observations of climate are often insufficient for characterizing future risks.

## Key Message 3.4

## Humans Are Changing Earth System Processes

Human activities cause changes throughout the Earth system, including the land surface, cryosphere, ocean and atmosphere, and carbon and water cycles. The magnitude, and for some processes the direction, of these changes can vary across regions, including within the US. These changes also occur against a background of substantial natural climate variability.

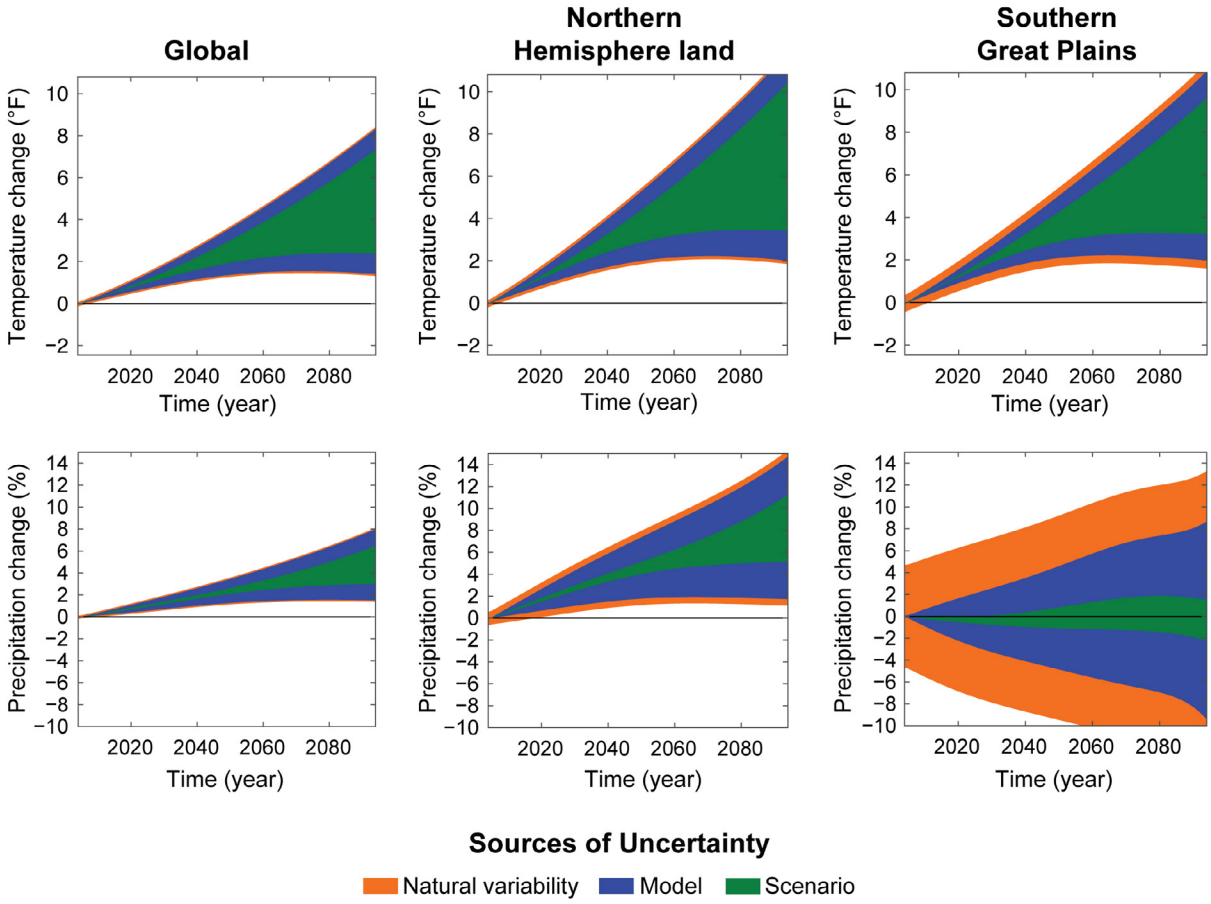
### *Natural Variability*

At all spatial scales, the climate response is forced by anthropogenic drivers, which are *external* to the climate system. This response occurs against a background of *natural* climate variability (i.e., *internal* to the climate system). Such variability is generated by natural processes, for example, by atmosphere–ocean interaction (e.g., El Niño and La Niña events), atmosphere–land interaction, or chaotic variability within the atmosphere itself. Depending on the sequencing and magnitude of natural variability and the magnitude

of the climate change response, natural variability can mask the climate change signal, amplify it, or be overwhelmed by it. Natural variability therefore adds uncertainty to climate change projections. Because the sequencing of natural variability is largely unpredictable, this component of uncertainty in climate change projections is irreducible. This is in contrast with the uncertainty associated with the climate change response, which arises from lack of information about future greenhouse gas and aerosol emissions, as well as incomplete understanding of climate processes and associated limitations in terms of how well models reproduced observed changes. These are knowledge gaps that can, in principle, be filled (KM 3.2).

The magnitude of natural variability generally increases as spatial scales decrease (Figure 3.6). At the scale of a typical Earth system model (ESM) grid cell, natural variability is the dominant source of uncertainty in precipitation and temperature projections over much of the US. On continental scales, model and scenario uncertainties become more important.[86] Therefore, at the regional scales and the multidecadal time horizons relevant for adaptation planning, uncertainty due to natural variability can be a larger contributor to overall uncertainty in climate change than model or scenario uncertainties (Figure 3.6; e.g., Dong et al. 2021[87]). Furthermore, it is important to note that anthropogenic forcing also changes the variability of some Earth system processes, and these forced changes contribute to changes in the frequency, duration, and intensity of extreme events, such as heatwaves and heavy precipitation.

## Natural Variability and Climate Model and Scenario Uncertainties




**The sources of uncertainty in climate projections vary depending on timescale and geographical scale and for different aspects of the climate system.**

**Figure 3.6.** These charts show the relative importance of different sources of uncertainty (natural variability, model uncertainty, and scenario uncertainty) for projections of moving decadal average temperature (**top row**) and precipitation (**bottom row**) for the globe (**first column**), Northern Hemisphere land (**second column**), and the Southern Great Plains (**third column**) from 1999 to 2099 (decadal averages are plotted mid-decade; for example, the x-axis starts in 2004) relative to the reference period of 1995–2014, based on CMIP6 models. Model uncertainty is calculated as the variance across models' forced response estimates. Scenario uncertainty is calculated as the variance across multimodel averages for different scenarios. The shadings are constructed as a symmetric 90% range around the multimodel, multiscenario average projection. Figure credit: Cornell University, National Center for Atmospheric Research, and Pacific Northwest National Laboratory.

## *Atmospheric Circulation Changes*

Past and future climate changes in the United States are strongly modulated by atmospheric circulation features such as the semipermanent North Pacific and North Atlantic subtropical high–pressure systems, the Aleutian Low, the meandering jet stream stretching from the North Pacific to the North Atlantic, extratropical storm tracks and fronts, and the North American Monsoon. These regional- to continental-scale circulation features are in turn modulated by even-larger-scale overturning circulations such as the Hadley cell (see Perlwitz et al. 2017[88]). Regional circulation features over North America are also modulated by recurring remote patterns of variability such as the El Niño–Southern Oscillation (ENSO) and North Atlantic Oscillation and by variability due to the chaotic dynamics within the atmosphere (the so-called butterfly effect).

Anthropogenic forcing alters the vertical and horizontal energy and moisture distributions in the atmosphere. Atmospheric circulation is directly impacted by the resulting changes in the temperature gradient from the equator toward the poles (both in the lower and upper troposphere), the decrease in the rate that temperature falls with height above the surface, and increased latent heating.

A synthesis of observational and modeling studies estimates that the tropics have widened by about 0.5° of latitude per decade since 1979. Although climate models driven by external forcing simulate, on average, a larger expansion rate than observed, the observed rate is within the bounds of the model simulations.[89] The discrepancy between the observed and simulated rates of tropical widening is partly due to patterns of natural variability such as ENSO and the Pacific Decadal Oscillation, as well as natural atmospheric variability.[90,91]

Consistent with the tropical expansion, climate models project poleward shifts of the jet streams and storm tracks and poleward expansion of the subtropical dry zones with warming,[88] with associated impacts on the US. However, the Northern Hemisphere jet shifts are regionally and seasonally dependent (e.g., Oudar et al. 2020;[92] Zhou et al. 2022[93]). Simulations show a poleward jet shift in the central North Pacific with warming, along with an eastward jet extension that steers more Pacific storms toward California.[94,95] However, large uncertainty remains because the jet extension is also influenced by natural variability.[87] With global warming shifting the North American westerly jet poleward throughout the warm season, climate models project late-spring wetting and late-summer drying in the Midwest.[96] Poleward expansion of the North Atlantic subtropical high may intensify and extend the Great Plains low-level jet poleward, affecting warm-season precipitation in the Midwest.[97]

Besides changes connected to the tropical expansion, climate models project a weakening of the North American Monsoon with warming due to increased atmospheric stability.[98] Similar to other monsoon systems, the onset of North American Monsoon rainfall is projected to be delayed by warming.[99,100,101] In the North Pacific, warming is projected to reduce the frequency of atmospheric blocking during winter.[102]

## *Water Cycle Changes*

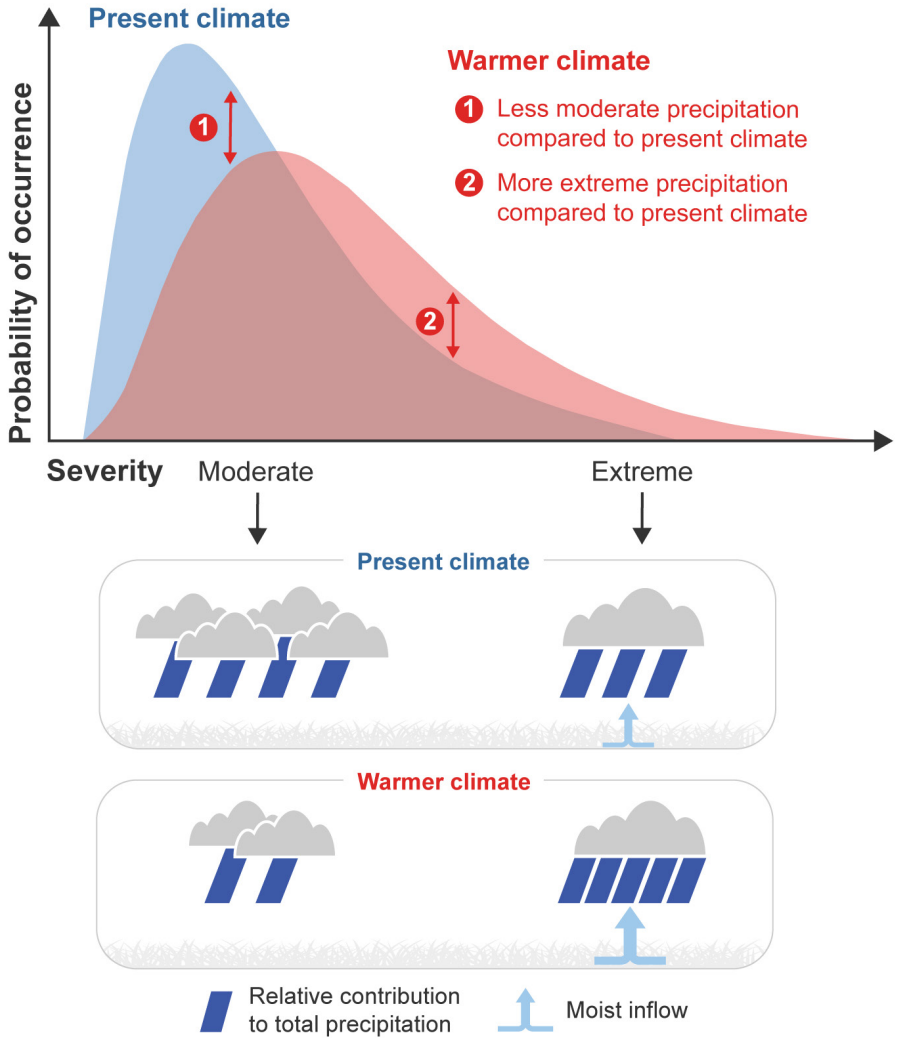
Many processes relevant to the water cycle have already begun to change and are projected to continue changing as the planet warms. These include the atmospheric circulation changes noted above as well as changes in atmospheric moisture, patterns of natural variability, the magnitude of variability of the water cycle, and the modulating role of vegetation on evaporation. These changes are driving changes in the intensity of precipitation in extreme events; snowfall, snowpack, and snow melt; and the seasonality of average precipitation and evaporation.

Seasonal and annual average precipitation and evaporation patterns have been changing with global warming. Precipitation from extreme events is projected to increase with warming (e.g., Neelin et al. 2017[103]). Heavy precipitation events constitute a large fraction of total precipitation and also a large fraction of the change in precipitation in both observations and projections.[104,105,106,107] However, it is possible to have increases in extreme precipitation but decreases in annual average precipitation at the same location due to large declines in non-extreme precipitation (Figure 3.7)[98,108,109] and overall changes in the variability of precipitation. Precipitation variability generally is projected to increase at all timescales and in most locations in response to anthropogenic forcing.[110] This implies increases in both heavy precipitation extremes and drought,[111] a phenomenon called whiplash.[112]

Water vapor factors into the intensity of precipitation extremes, such that increased water vapor due to warmer air temperatures alone would drive relatively uniform projected increases in precipitation extremes over much of the planet. Additionally, changes in circulation modulate the spatial pattern of extreme precipitation intensity change, increasing it in some regions and reducing it in others.[113] For extratropical cyclones

in summer, precipitation intensity increases, and more energetic convective storms are projected despite weakening circulation.[114] While understanding of these changes in extreme precipitation has improved, recent work has also highlighted the oftentimes large magnitude of natural variability in extreme precipitation (KM 3.5).

## Changes in the Contributions of Moderate and Extreme Events to Total Precipitation with Warming




**As the climate warms, extreme precipitation events become more intense and make up a larger fraction of total precipitation, while moderate events become less common.**

**Figure 3.7.** The graphic depicts example changes in the precipitation distribution at many locations as projected by climate models. (**top**) In general, warming shifts the distribution toward a greater probability of large events and a reduced probability of light to moderate events, with only a modest change in the average total precipitation over a season or year. (**bottom**) Greater levels of water vapor in the atmosphere in a warmer world drive more precipitation during storms, when moist air masses converge. The increased water vapor convergence, or moist inflow, in very stormy areas also transports more water vapor out of surrounding areas, reducing any light to moderate precipitation there. The changes in total precipitation are often modest, because they reflect this tug-of-war between opposing changes in heavy and light to moderate precipitation. Changes in circulation can also affect the changes in all parts of the precipitation distribution. Certainty in projected changes differs among the underlying processes: the increase in water vapor and associated increase in extremes is very certain, while the changes in circulation are less certain. Further discussion related to top panel can be found in Fischer and Knutti (2016).[115] Figure credit: Cornell University and University of California, Los Angeles.

Changes in precipitation seasonality can occur with or without changes in average annual total precipitation. Increases in the amplitude of the precipitation seasonal cycle may be expected, as precipitation increases proportionally to its present-day seasonal cycle. However, other changes in the seasonal cycle of precipitation have also been found. Examples of these changes include a sharpening of the seasonal cycle in California,[112,116,117] a substantial increase in late-spring precipitation and a substantial decrease in late-summer precipitation in the US Midwest,[96] and a delayed onset of rainfall in many monsoon regions.[100,101]

Even if precipitation increases in some regions in the future, one concern is that evaporation will increase with warming, leaving the land surface drier (also see Ch. 4). Model projections and observational analyses for the US suggest that the net effect will be for warming to increase evaporation and surface drying in much of the country.

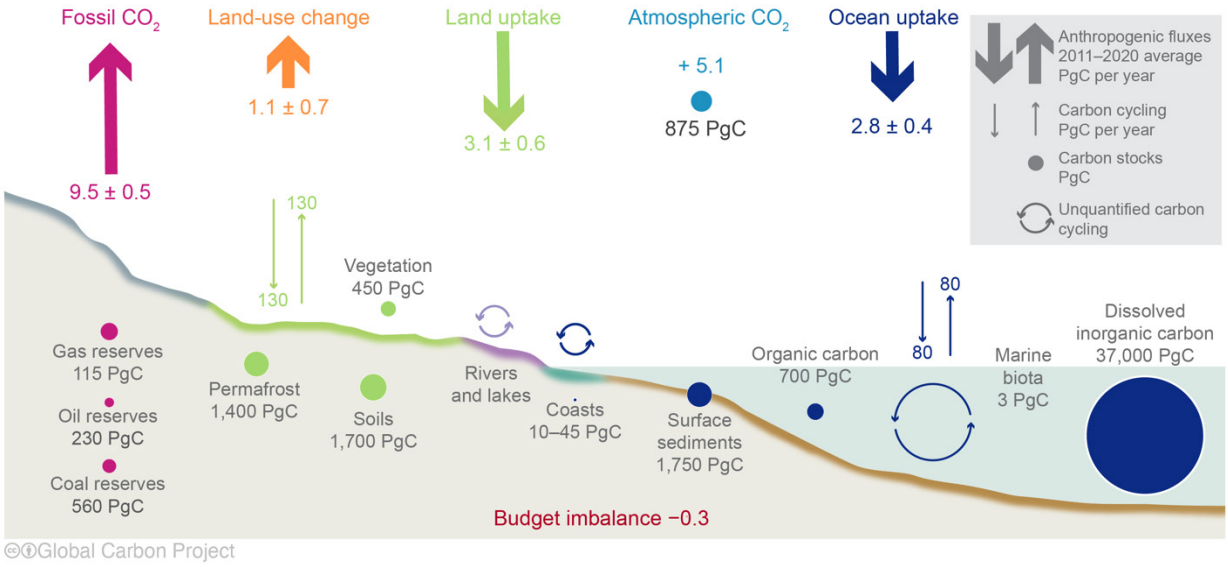
With warming temperatures, more precipitation falls as rain instead of snow. Snowpack in many mountainous regions of the US has already decreased on average over the last few decades; for example, the western US snowpack-driven reservoirs are already exhibiting changes.[118] These declines are expected to be exacerbated by greater increases in winter temperatures compared to summer temperatures in some regions due to snow albedo feedbacks. Another factor that decreases snowpack is the larger temperature increases at higher altitudes, which increase the frequency of multiyear snow droughts.[119] Decreases in warm-season streamflow have also been observed and projected because of the increase in evaporation with warmer temperatures.[120,121,122] Decreasing snowpack and increases in flooding are both concerns for water management. Increasing flooding is driven by the increasing intensity of extreme precipitation discussed above, by the shift from snowfall to rainfall, and potentially also by increases in rain-on-snow events, which can lead to rapid snowmelt (for one example, see Box 29.2).

## *Changes in the Carbon and Biogeochemical Cycles*

Understanding of the biogeochemical responses to human-caused greenhouse gas emissions has increased due to expanded observations and improvements in models. However, uncertainty in the future evolution of the global carbon cycle remains high (KM 2.3).

Terrestrial ecosystems and the oceans take up a little more than half of the $CO_2$ emitted from human activities, partially offsetting the climate effects of carbon emissions. From 2011 to 2020, annual emissions averaged 10.6 ± 1.2 PgC, and the emitted carbon was ultimately distributed between the atmosphere (47%), vegetation and soils in terrestrial ecosystems (29%), and the oceans (24%; Figure 3.8).[123] Over the past six decades, the average fraction of anthropogenic $CO_2$ emissions that has accumulated in the atmosphere has remained nearly constant at 41%, even as fossil fuel emissions have rapidly increased.

## Carbon Dioxide Sources and Sinks




**While the land and ocean take up some of the carbon dioxide from human activities, the rest continues to accumulate in the atmosphere every year.**

**Figure 3.8.** The primary sources of anthropogenic carbon are fossil fuel and land-use change emissions (upward thick arrows). While the land biosphere and ocean continue to take up the same proportion of anthropogenic carbon every decade (downward thick arrows), atmospheric carbon dioxide ($CO_2$) levels continue to rise as fossil fuel and land-use change emissions continue over time. Represented here is the budget of the global carbon cycle each year from estimates averaged globally for the decade 2011–2020, with flux estimates from Canadell et al. 2021.[4] Values are in Petagrams of carbon (PgC). Adapted from Friedlingstein et al. 2022[123] [CC BY 4.0].

An important question is whether the same fraction of fossil fuel emissions will continue to be offset by ocean and land biosphere uptake or whether the offset will slow or reverse over time. Answering this question depends on understanding feedbacks between the carbon cycle and climate change. The additional carbon sink on land is a consequence of multiple ecosystem processes, including increased photosynthesis responses to rising atmospheric $CO_2$,[124] nitrogen deposition, fire suppression, and forest regrowth after disturbances such as land clearing for agriculture.[125] Large-scale observational constraints on increased vegetation productivity due to increased atmospheric $CO_2$ are uncertain.[126] Ocean waters take up an increasing amount of carbon due to chemical dissolution of $CO_2$ in seawater, biological fixation through photosynthesis, shell formation in some organisms, and subsequent transport of carbon into deeper waters.

As atmospheric $CO_2$ increases, plant productivity and soil carbon also increase and are partly responsible for increases in land carbon storage, which functions as a negative feedback on climate change. However, several processes could reduce terrestrial carbon uptake, including increasing temperature and drought frequency or intensity, limitation of other necessary nutrients, and land-use changes such as deforestation. In the Arctic, potentially large biogenic releases of $CO_2$ and $CH_4$ to the atmosphere due to permafrost thaw—the timing of which may be accelerated by increasing wildfire at high latitudes[127]—could be a potentially large positive climate feedback that may alter the effectiveness of climate mitigation strategies.[128] ESMs predict a total loss of near-surface permafrost by 2100 for intermediate (RCP4.5) and very high (RCP8.5) emissions scenarios, and permafrost carbon emissions are projected to outpace increased carbon uptake from higher vegetation productivity in a warmer Arctic.[129]

Uptake of $CO_2$, an acid gas, by oceans leads to acidification of seawater through a series of chemical reactions that lower the pH and availability of carbonate ions in addition to other chemical changes (see

Chapter 2 for ocean acidification trend) that have been shown to be harmful to marine life.[130] Over time, uptake of carbon could slow as ocean waters become saturated with dissolved $CO_2$.[131] Recent observations show that ocean carbon processes are starting to change in response to the growing ocean carbon sink, and these changes are expected to contribute to future weakening of the ocean carbon sink under medium to high emissions scenarios (similar to SSP2-4.5 and SSP5-8.5 of Figure 3.7 in Jiang et al. 2019[132]).[133]

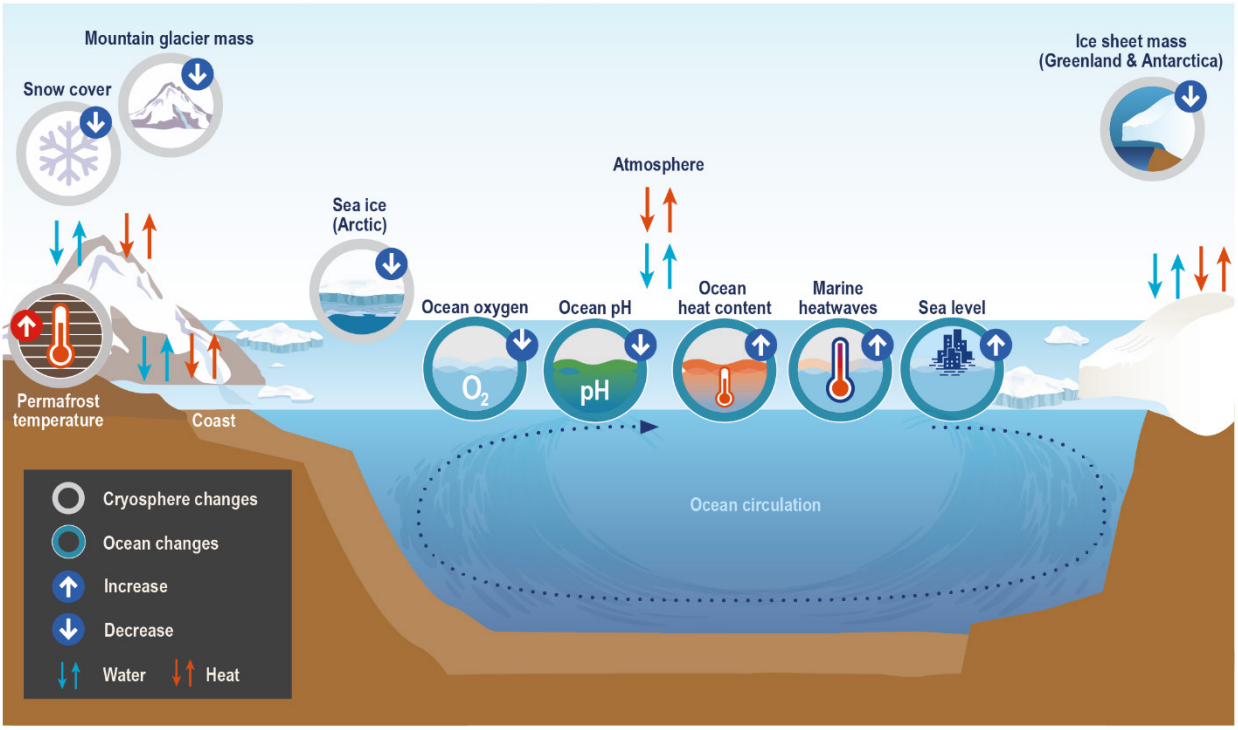
A comparison between the CMIP5 and CMIP6 generation of ESMs with respect to the representation of the $CO_2$ fertilization effect and carbon cycle–climate feedbacks suggests that uncertainties in these processes have remained large and virtually unchanged in recent years.[134] However, the latest generation of land models have improved representation of biogeochemical cycles,[4] and ocean models have exhibited improved representation of coupled physics and biogeochemical cycles.[135]

In the United States, the land carbon sink is dominated by forests, which have expanded in the last century due to fire exclusion in the West and to secondary forest regrowth following agricultural abandonment in the East. The growth of the North American forest biomass carbon sink is expected to become more saturated and less effective over time (Focus on Western Wildfires).[125,136] The climate change–wildfire relationship is also expected to play an increasingly dominant role in the strength of the US land carbon sink, requiring increased management of forests to meet carbon storage and other needs of society.[137] In addition, increasing temperature and moisture in some regions could lead to increased microbial emissions of $CH_4$ from wetlands and Arctic tundra.

## *Changes in the Ocean*

The ocean has a large capacity to store and release heat and has been able to absorb 91% of the excess heat attributed to greenhouse gas emissions.[2] The ocean both exchanges heat with the atmosphere and moves heat from the tropics toward polar regions, where warm surface ocean waters transform into cooler, high-density waters that sink (Figure 3.9),[138] taking high carbon concentrations with them.[139] The Atlantic Meridional Overturning Circulation (AMOC) is an important component of the global ocean circulation, transporting heat and carbon and affecting hydroclimate, hurricane activity, and coastal sea level. It is hypothesized from some proxy evidence that the AMOC has declined since the Industrial Revolution.[140] It remains uncertain whether observations support the anthropogenically forced weakening of the AMOC during the past four decades predicted by climate models.[141]

## Changes in Ocean, Cryosphere, and Coastal Processes




**Climate change has multiple effects on the ocean, atmosphere, and cryosphere and their complex interactions.**

**Figure 3.9.** The figure shows important physical processes that play a role in the ocean and cryosphere, along with their linkages. Associated climate change–related effects, including sea level rise, increasing ocean heat content, ocean acidification, marine heatwaves, and ice mass loss, are also shown. The arrows indicate an exchange taking place between ice, ocean, and atmosphere. Adapted with permission from Figure TS.2 in IPCC 2019.[142]

On short timescales (annual to decadal), ocean circulation dominates the pattern of changes in ocean heat content; although on longer timescales, the spatial pattern is primarily associated with the addition of excess heat into the ocean.[143] Since 2005, Argo profiling floats have provided observations of temperature and salinity changes in the global ocean to a depth of 2,000 m. These measurements show an increase in global ocean heat content, although there is geographic variability. On shorter timescales, marine heatwaves are periods of extreme high ocean temperature relative to the long-term average seasonal cycle.[144] Persistent marine heatwaves have been observed in the northeastern Pacific since around 2014,[145,146,147] with associated negative impacts on ocean ecosystems (Ch. 27; Figure 10.2).

## *Changes in the Cryosphere*

The cryosphere is the frozen part of the Earth system and includes ice sheets, glaciers, sea ice, permafrost, and snow (Figure 3.9). Observations of the cryosphere have expanded in recent years, including from satellites like Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) and Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2).[148] These and other complementary observations of the cryosphere show declines in ice sheet and glacier mass, snow cover, and Arctic sea ice.[149] Through efforts like the Ice Sheet Mass-Balance Inter-comparison Exercise (IMBIE),[150] there is clear evidence of loss of ice sheet mass from 1993 to 2020, and the rate of loss has increased for both the Greenland and Antarctic ice sheets. There is increased consensus regarding the behavior of many ice sheet processes. However, as the climate warms, the future response of the ice sheets and some associated processes are still uncertain.[149] Two specific processes, marine ice cliff instability[151,152] and marine ice sheet instability,[153,154,155,156,157] could lead to rapid

ice sheet loss over several decades, but the physical processes that would result in these instabilities and how they would progress once triggered remain uncertain. The decline in sea ice affects several critical functions: sea ice serves to regulate climate by reflecting solar radiation; inhibits ocean–atmosphere exchange of heat, momentum, and gases; and supports global deep-ocean circulation, polar species, and livelihoods of people in the Arctic.

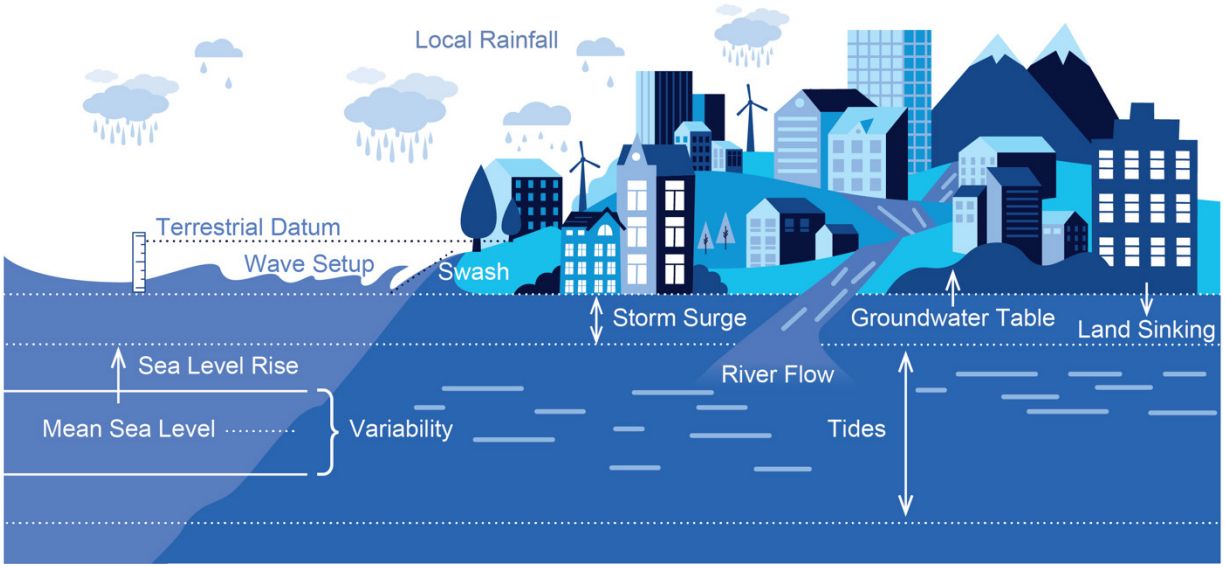
## *Sea Level Rise*

Over long time periods, the main drivers of changes in global mean sea level (GMSL) are thermal expansion due to heating of the ocean and the addition of water associated with melting ice from ice sheets and glaciers. Human-caused changes in the movement of water between ocean and land, including from groundwater depletion and water impoundment associated with dam building, have a minor impact on GMSL, although they can increase in importance for specific time periods.[158] The increase in GMSL during the 20th century estimated from tide-gauge records has been explained by the individual processes contributing to it.[158] The rate of the 20th-century increase in sea level was faster than in any other century in at least the last 3,000 years.[159,160] In the past two decades, the changes in GMSL measured by satellite altimetry have matched the expected sea level rise based on the combination of in situ measurements of the Argo profiling floats and the observations of water-mass change from the GRACE and GRACE-FO satellites. Data from the now three-decades-long satellite altimetry record shows that the rate of GMSL rise has been increasing, driven by accelerating contributions from the underlying processes.[158,161,162]

Sea level rise is not uniform across the globe. Relative sea level rise at any specific location responds to processes that are important at regional and local scales.[149,163,164,165] On short timescales and in short records, natural variations on interannual to decadal timescales can affect estimates of rates and accelerations. Over long time periods, there are three main causes of regional variations in relative sea level: 1) sterodynamic changes (the combination of thermal expansion and ocean dynamics that is driving global sea level rise); 2) gravitational, rotational, and deformational changes that result from water moving from the cryosphere to the ocean; and 3) vertical land movement (subsidence or uplift) due to glacial isostatic adjustment, tectonics, sediment compaction, groundwater and fossil fuel withdrawals, and other non-climatic factors.[166,167]

An improved understanding of the drivers of regional mean sea level rise and how processes combine to cause sea level change at the coast has led to better assessments of the frequency, duration, and timing of high-water levels and coastal flooding events (Figure 3.10).[167] Regional sea level change has been the main driver of changes in extreme water levels.[167] Due to ongoing regional relative sea level rise and narrowing of the gap between the typical high tide and flooding threshold, the frequency of high tide flooding has increased. Natural ocean variability, including that associated with tides and large-scale climate signals that did not necessarily result in flooding in the past, is expected to lead to a rapid increase in the amount of high tide flooding in the coming decades when combined with future sea level rise (see Ch. 9).[167,168,169]

### Coastal Flood Exposure



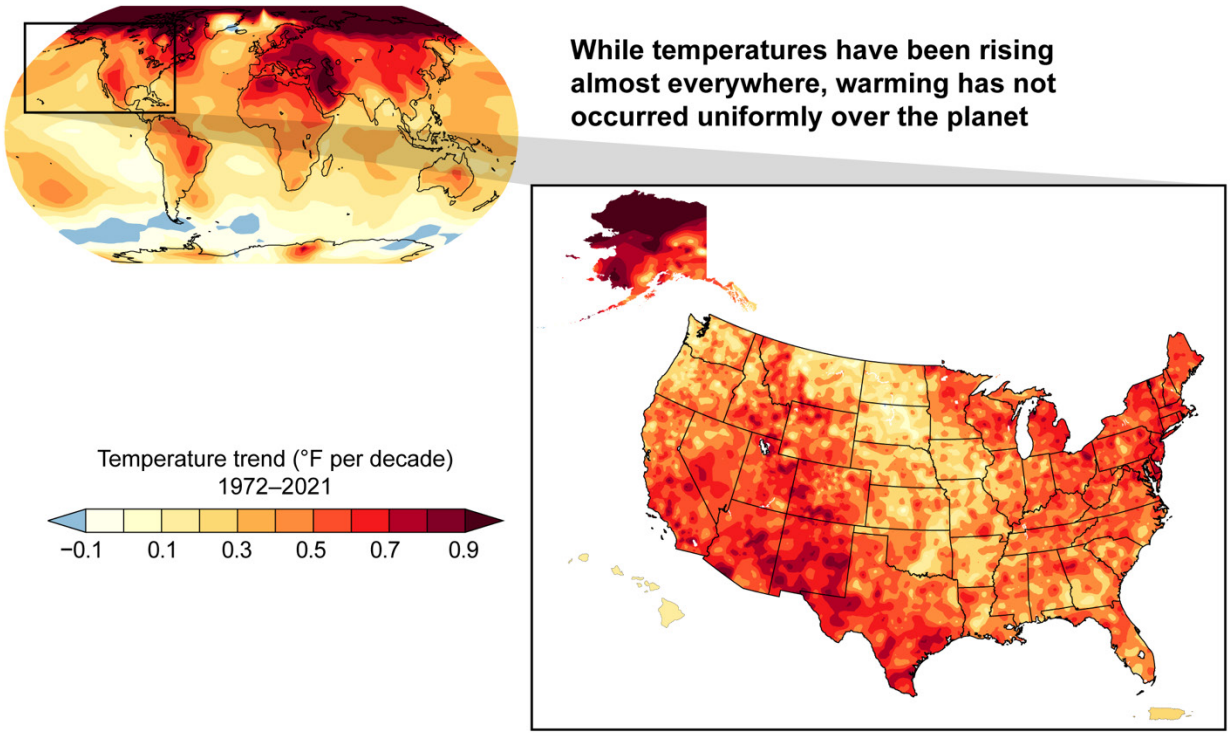

**Sea level rise is increasing the probability of coastal flooding and associated impacts.**

**Figure 3.10.** The schematic shows the physical factors affecting coastal flood exposure. Nearshore processes like storm surge, wave setup (the increase in water level due to the presence of breaking waves), and swash (wave runup and wave rundown) combine with other large-scale processes to drive impacts. Due to the clear and strong relative sea level rise signal—that is, the combination of global increases in sea level and the fact that land is sinking in many US coastal areas—the probability of flooding and impacts is increasing along most US coastlines. Source: Sweet et al. 2022.[167]

## *Regional-Scale Changes*

Many of the changes in Earth system processes discussed above can vary across a range of spatial scales. For example, at the continental scale (less than 10,000 km), the climate system's warming response to anthropogenic forcing is affected by differences in how quickly land and ocean areas warm, with land generally warming more quickly than the ocean. This is because land areas have a lower heat capacity and thus respond more quickly than the ocean to anthropogenic forcing, and because of the larger cooling effect of evaporation from the ocean surface. Therefore, North America generally warms more than adjacent oceans (Figure 3.11). The high latitudes of the Northern Hemisphere warm the most of any region, although the reasons for this are complex and may involve processes poorly captured by global climate models.[170] Precipitation responses, arising from the changes in the atmospheric circulation and water cycle processes discussed above, tend to be organized in latitude bands such as the tropics, subtropics, midlatitudes, and high latitudes.

## Regional Differences in Climate Response




**While temperatures have been rising almost everywhere, warming has not occurred uniformly over the planet.**

**Figure 3.11.** The maps show observed global (**left**) and overland US (**right**) trends (in °F per decade) in annual average near-surface temperature over the period 1972–2021. While temperatures have been increasing almost everywhere, warming has not occurred uniformly over either the planet or the US. Temperatures over land have been increasing faster than over the ocean, and the Arctic has been warming at more than twice the global average rate. Temperatures over the US have increased faster in Alaska, at high elevations, and in regions with significant seasonal snowpack. Figure credit: University of California, Los Angeles; University of California, Davis; NOAA NCEI; and CISESS NC.

At the regional scale (less than 1,000 km), variations in land surface properties are associated with differences in the local climate responses to anthropogenic forcing. Examples from the US (Figure 3.11, US panel) include greater warming at snow margins in western US mountains,[171] greater warming in inland areas separated from the coast by California mountain ranges,[172] greater warming in extremely arid landscapes,[173] shifts of precipitation downwind in mountainous areas,[174] snowfall loss at higher elevations where temperatures increase above the freezing line,[175,176] changes in snowmelt-driven runoff as a function of elevation,[177] changes in snowfall over large lakes,[178] and changes in evaporation and soil moisture due to variations in vegetation. Regional variations in the changes of temperature and precipitation are also driven partly by the regional distributions of aerosols, which interact with clouds and radiation.[179] Downscaling techniques, which convert global model outputs from lower resolution (about 100 km) to high resolution (1–10 km), are often used to simulate these phenomena for adaptation planning (see App. 3).

## Key Message 3.5

## Humans Are Changing Weather and Climate Extremes

Human activities are affecting climate system processes in ways that alter the intensity, frequency, and/or duration of many weather and climate extremes, including extreme heat, extreme precipitation and flooding, agricultural and hydrological drought, and wildfire (*medium* to *high confidence*).

### *Extreme Heat and Cold*

Changes in temperature extremes in recent decades are driven primarily by trends toward warmer conditions rather than any changes in variability.[180] Consequently, the frequency and intensity of cold extremes have declined over much of the United States while the frequency and intensity of extreme heat have increased.[181] Arctic warming may also drive increases in the occurrence and persistence of circulation anomalies that are related to extreme cold and heat,[182] although the evidence that these mechanisms have played a role in recent events is mixed.[183,184] Climate change may also be contributing to "false spring" events,[185] where early warming has caused early budbreak and flowering of plants, exposing them to damaging frost and freeze events.[186]

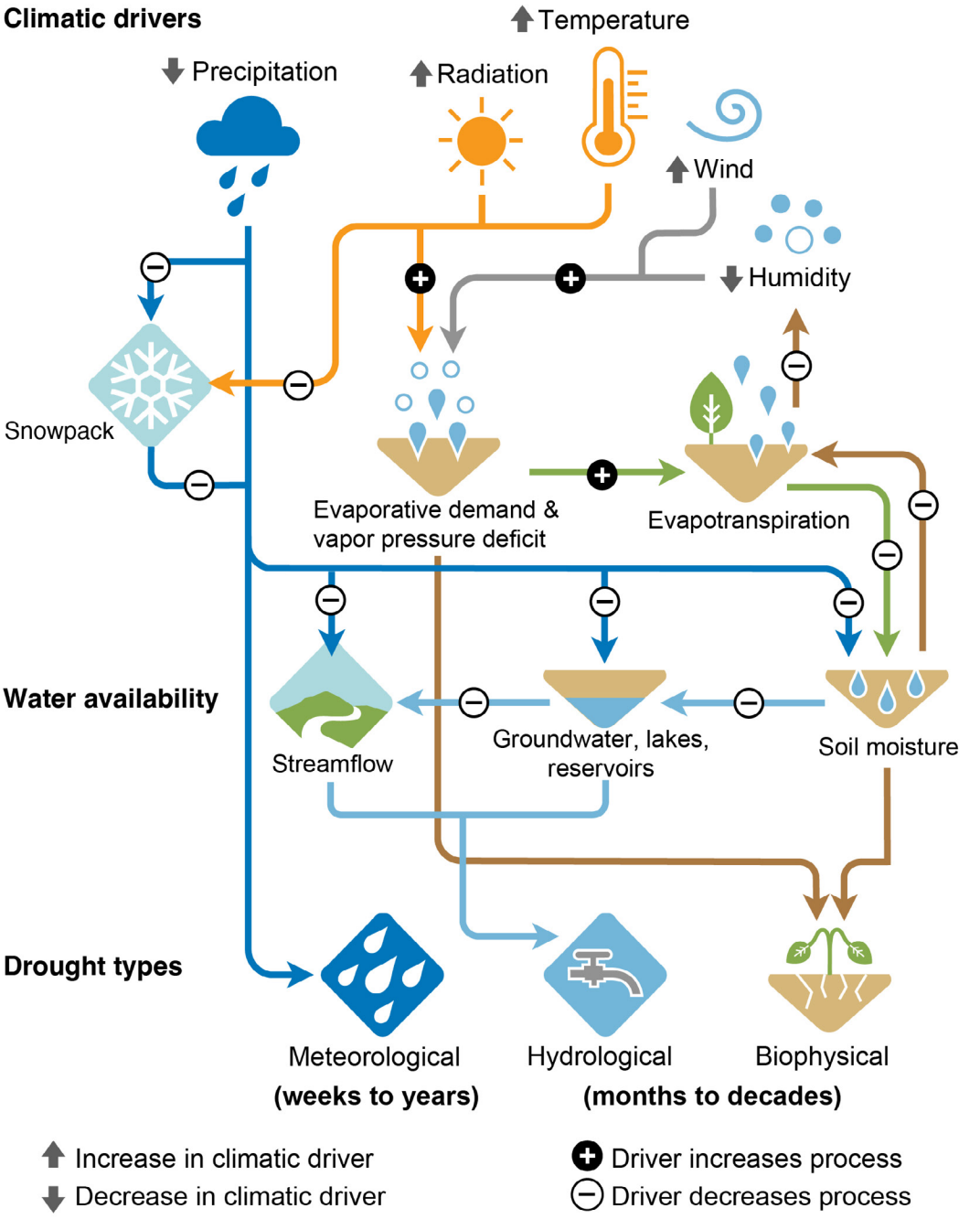
### *Extreme Precipitation and Flooding*

Observed increases in extreme precipitation intensity at the continental scale in North America have been, for the first time, attributed to human influences.[187] With warming, it is expected, and has been documented, that more winter precipitation will fall as rain instead of snow,[188] although the projected intensity of most extreme snowstorms remains uncertain.[189] Projected increases in extreme precipitation events are larger in the winter season since warming in winter is larger, including events related to atmospheric rivers.[190] Precipitation associated with hurricanes increases with warming at least as much as water vapor,[42] and the heaviest events can increase at an even greater rate.[63,191,192] Where and when increases in extreme precipitation manifest in any given year or even decade is strongly subject to natural variability (see also KM 3.3). Notably, increases in extreme precipitation events do not always directly translate to increases in river flooding, in part because of the many processes at the land surface that affect flood events (KM 4.1; Figure 4.8).

### *Drought*

Drought is broadly defined as a transient period of below-average water availability, typically expressed in terms of fluctuations in precipitation, soil moisture, or streamflow and runoff.[193] Drought is a complex phenomenon (Figure 3.12) that depends on fluctuations in moisture supply, direct losses of moisture to the atmosphere, and ecosystem and land surface processes.[194,195,196] Western North America experienced several decadal-scale droughts during the 20th century[197] and numerous multidecadal "megadroughts" prior to AD 1600[198] and is currently experiencing an ongoing megadrought largely unprecedented over the last 1,200 years.[199,200] See Chapter 6 for more information regarding the effect of changes in the water cycle over land.

## Climatic Drivers of Drought, Effects on Water Availability, and Impacts




**Climate change alters the hydrologic cycle and is expected to increase drought in some regions through various process pathways.**

**Figure 3.12.** Changes in climatic drivers (e.g., precipitation, temperature, wind, etc.) affect different aspects of the hydrologic cycle (e.g., evapotranspiration, snowpack, streamflow, soil moisture). In turn, these hydrologic shifts translate into changes in the severity, frequency, and risk of different drought types. Plus and minus signs denote the direction of change in the driver that would cause increases in drought. For example, where precipitation declines (down arrow), all drought types will increase because this reduces snowpack, streamflow, groundwater and reservoir storage, and soil moisture. Similarly, increasing temperatures (up arrow) are also expected to increase hydrological and biophysical drought by reducing snowpack and increasing evaporative losses from streams, surface reservoirs, and soils. Adapted with permission from Figure 8.6 in Douville et al. 2021.[201]

Observed and projected hydroclimatic changes in response to external forcing are highly season- and region-dependent over the US, especially in the West.[202] Natural variability also plays a prominent role in shaping hydroclimate on annual and decadal timescales,[203] as indicated by the decrease in total area coverage of low soil moisture over the US since 1915[204] and increasing Missouri River flows,[205] a region that is expected to become drier under climate change (e.g., Cook et al. 2015[206]). Climate change is expected to amplify drought, primarily through warming-induced increases in evaporative demand and surface water losses[207,208] and declines in snowfall and water stored in winter snowpack.[43] There is strong evidence that these processes are already amplifying hydrological drought severity in California,[209,210,211] the Pacific Northwest,[212,213] the Colorado River basin,[121,214] and across southwestern North America.[200] However, there are uncertainties in how these processes may present in the future. For example, changes in plant water use in response to increasing temperatures and rising atmospheric $CO_2$ are complex and poorly understood and may either ameliorate[195] or amplify[215] soil moisture and runoff droughts at the surface.

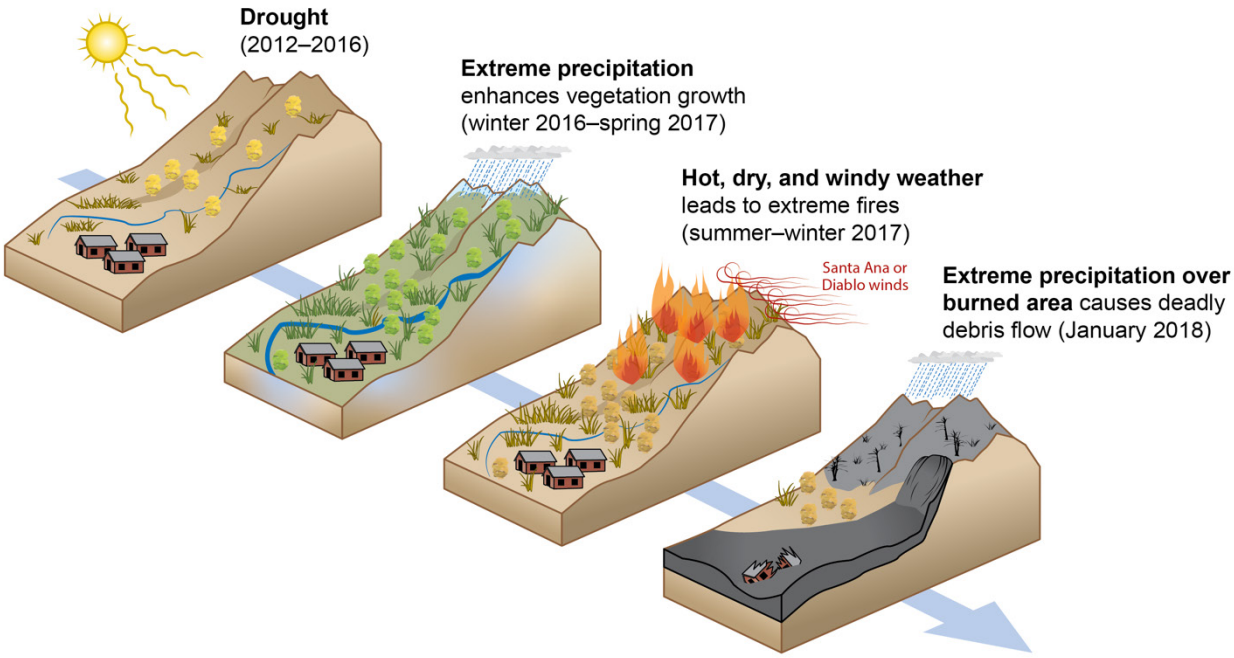
## *Wildfire*

The direct influence of climate change on modern and future wildfire activity arises from the effect of warming on fuel moisture content and flammability (Focus on Western Wildfires). Flammability is directly related to the vapor pressure deficit (VPD), an integrative measure of atmospheric aridity or dryness. High VPD is strongly associated with the hot and dry weather conditions conducive to the intensification and spread of wildfires, as well as with drier fuels at the surface. In recent decades, warmer temperatures, declines in humidity, and increases in VPD have caused large-scale increases in fire weather[216] and areas burned by wildfire[217,218,219] across the West. From 1984 to 2015, about half of the increase in burned area across the western United States is attributable to increases in fuel flammability caused by anthropogenic climate change. These climate change–driven increases in wildfire burned area are expected to continue into the coming decades, as fuel availability is not expected to be a limiting factor before 2050.[220]

## *Compound Events*

Compound events refer to the combination of multiple weather or climate events—which individually may not be extreme—that together pose risks to human or natural systems (see example in Figure 3.13)[221,222,223] and are described in further detail in Focus on Compound Events. Since climate change may affect the frequency and magnitude of the individual components of compound events in different ways, changes in compound events can be complex. Recent advances in statistical techniques used to describe compound events[224,225,226,227] offer rigorous ways to quantify changes. Progress has also been made in categorizing compound event types in this rapidly evolving field.[223,228,229]

## Consecutive Events Leading to and Resulting from Wildfires




**Consecutive events caused significant human health and economic impacts in Southern California from 2012 through 2018.**

**Figure 3.13.** A series of events in Southern California produced a cascade of impacts on human health and the economy. These include (from top left to bottom right): a prolonged drought from 2012 to 2016; above-average winter precipitation in 2017, enhancing growth of fuels; a dry, warm spring and summer, reducing moisture levels and drying existing vegetation; record-setting Santa Ana winds; fires occurring shortly thereafter; and rainfall over the burned area, leading to debris flow event in Montecito, CA. Adapted from AghaKouchak et al. 2020;[230] modified with permission from the Annual Review of Earth and Planetary Sciences, Volume 48 © 2020 by Annual Reviews, http://www.annualreviews.org.

# Traceable Accounts

## *Process Description*

Team members were selected from two sources: 1) the pool of nominations received via the public call for authors and 2) candidates identified by the chapter lead author, federal coordinating lead author, and agency coordinating authors from their extended networks and recommendations they received. The team was selected based on a thorough review of nomination packages received, with diversity of background and experience being a primary evaluation criterion for team makeup. Considering the areas of expertise needed for the chapter, as summarized below, selections were made to ensure diverse representation across multiple axes.

- Long-lived and short-lived climate forcers and biogeochemical cycles
- Land-use and land-cover change and biogeochemical cycles
- Climate response and internal variability
- Scenario development
- Climate feedbacks and response
- High-resolution modeling
- Regional climate change
- Climate model diagnostics and metrics
- Extreme event attribution
- Cryosphere and sea level rise
- Precipitation variability and extremes
- Drought and paleoclimate
- Hydrologic and heat extremes

Given that the scoping of this chapter is related solely to physical system processes and not impacts, risks, and vulnerabilities, it was determined early on in the process, and with the consent of the Federal Steering Committee, that stakeholder engagement meetings were not required for the data-gathering process. Authors communicated primarily through email and bimonthly (twice per month) team meetings to discuss chapter progress and any issues arising during the assessment of the literature.

## Key Message 3.1

## Human Activities Have Caused the Observed Global Warming

### Description of Evidence Base

Evidence of human drivers of global warming is provided by identifying the human-induced components that perturb Earth's energy budget and by understanding how these have evolved over long timescales. The potential for surface warming due to increases in carbon dioxide ($CO_2$) emitted from human activities was first identified in the 1800s,[231,232,233] and scientific understanding of the effect of anthropogenic $CO_2$ emissions on the climate strengthened with more than a century of advances in theoretical developments as well as through laboratory and in situ measurements.[234] The effect of other human drivers on climate, including non-$CO_2$ greenhouse gases (GHGs), land-use change, and aerosols, was also recognized by the 1970s. Assessment of multiple lines of evidence, including proxy records, ice core records, and direct observations,

provides unequivocal evidence of the role of human activities in increasing atmospheric levels of GHGs and aerosols over the industrial era. For the latest observational evidence of long-term changes in GHG abundances, the reader is referred to Figure TS.9 in the IPCC AR6 WGI Technical Summary,[13] which shows a strong increase in well-mixed greenhouse gases since the 19th century that is exceptional over the long term. Global average annual anthropogenic emissions of these gases reached the highest levels in human history over the present decade based on assessment of multiple lines of evidence.[4]

Human-induced emissions of GHGs alter the atmosphere's radiative balance and lead to a climate response. Earth system model simulations reproduce the observed global surface temperature trend only when human-induced climate drivers are included. Multimodel attribution experiments in support of the different phases of the Coupled Model Intercomparison Project (CMIP) have consistently shown the majority of the observed global warming to be human-induced, while that attributable to natural drivers is small.[235]

## Major Uncertainties and Research Gaps

Although there is *very high confidence* in the measured increases in atmospheric GHGs since preindustrial times, attributing these increases to anthropogenic emissions or natural emissions is subject to some uncertainty (e.g., Saunois et al. 2020;[236] Tans 2009[237]). Fossil fuel emissions of $CO_2$ have the lowest uncertainty because of the direct relationship between combustion and emissions. Since radiocarbon ($^{14}CO_2$) is absent in fossil fuels, measurements of atmospheric $^{14}CO_2$ can be compared to $CO_2$ emissions inventories based on fuel consumption. Comparisons show agreements within the uncertainty bounds of the measurements.[238] However, there are discrepancies between different methods for quantifying $CO_2$ emissions and uptake related to land-use changes, the size of land uptake in the northern extratropics, and the strength of the ocean carbon uptake over the past decade.[123] For land-use change, a lack of historical land-cover information presents an important limitation. Likewise, inadequate coverage of datasets used to inform models of carbon exchanges between the biosphere and oceans and the atmosphere results in uncertainty for both process-based models and atmospheric inversions.

For methane ($CH_4$) emissions and removals, uncertainties are potentially larger than for $CO_2$. Emissions of $CH_4$ are usually the result of unintentional leakage from oil and gas infrastructure or the result of microbial processes that result from agriculture, livestock, or waste treatment. This unintentional leakage makes quantifying emissions using inventory methods difficult. However, measurements of the stable isotope of $CH_4$ ($^{13}CH_4$) imply that microbial sources are the primary drivers of recent atmospheric $CH_4$ growth, with smaller contributions from fossil fuel production. Measurements of $^{13}CH_4$ provide insight into sources, because microbes prefer to use the lighter carbon isotope ($^{12}C$) for metabolism, so an increase in microbial sources will mean isotopically lighter atmospheric $CH_4$. Although the atmospheric record of $CH_4$ ($^{13}CH_4$) only extends over the last two decades, measurements from ice cores suggest that prior to the recent trend toward isotopically lighter atmospheric $CH_4$, the trend was toward isotopically heavier $CH_4$, as expected due to isotopically heavier fossil fuel emissions.

Other important sources of uncertainty include difficulty in constraining atmospheric chemical destruction and uncertainty in the distribution and processes determining natural emissions. Studies comparing bottom-up estimates of emissions using inventories and emissions models with estimates from atmospheric inversions highlight uncertainties in the estimates.[236] Other studies using atmospheric observations of stable isotopes of $CH_4$ have suggested that global fossil fuel emissions are, in all probability, higher than those estimated by inventories.[5,239]

## Description of Confidence and Likelihood

There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have unequivocally caused all global warming observed over the industrial era. There is also *very high confidence* that changes in natural climate drivers have had globally small and regionally variable long-term effects over

this period. Observations clearly show that concentrations of major GHGs have increased in the atmosphere since preindustrial times. Uncertainties in natural chemical removals and emissions can be significant. Sporadic changes in natural climate drivers, including solar activity and volcanic eruptions, temporarily influence surface temperatures. However, reconstructions and proxy records do not indicate any evidence of exceptional activity in these climate drivers over the past several hundred years.[10] In sum total, uncertainties in the magnitude and variability of climate drivers are not expected to change the central conclusion that anthropogenic emissions have caused the significant increases in GHGs.

## Key Message 3.2

## The Estimated Range of Climate Sensitivity Has Narrowed by 50%

### Description of Evidence Base

The assessment of climate sensitivity and climate feedbacks follows that of Sherwood et al. (2020)[21] and Forster et al. (2021),[2] which were subject to review by peers and the community. In this Traceable Account, we provide a summary of the evidence base, major uncertainties, and a description of confidence and likelihood following these assessments. As also shown in Figure 3.3, the major change in these new assessments is to primarily base climate sensitivity estimates on observational data from multiple past periods combined with physical constraints, without directly using the values of climate sensitivity produced by climate models. Satellite observations of natural climate variability were used to provide global estimates of physical climate feedbacks,[240,241] as well as the cloud feedbacks for individual cloud types.[24,242,243,244,245] For many climate feedbacks, emergent constraints[240,246,247] support the practice of inferring long-term climate feedbacks from short-term climate feedbacks inferred from observations of present-day natural climate variability. For changes between the preindustrial period and present day, temperature analyses of in situ data provide confident estimates of global mean temperature changes.[248,249] Combining these temperature changes with estimates of effective radiative forcing for this period yields a preliminary estimate of climate sensitivity acting over the historical period. This preliminary estimate is now thought to be an underestimate of the climate sensitivity for $CO_2$ doubling because climate feedbacks are sensitive to the pattern of sea surface temperature warming, and the pattern of warming in the historical period differs markedly from that expected for doubling of $CO_2$.[173,250] Inferring climate sensitivity from paleoclimate changes relies on accurate estimates of temperature and radiative forcing changes for well-studied stable periods in the past, such as the Last Glacial Maximum (~20,000 years ago),[251] the Mid-Pliocene Warm Period (~3 million years before present),[252] and the Paleocene–Eocene Thermal Maximum (~56 million years before present).[253] To estimate a present-day climate sensitivity from paleoclimatic data, estimates of changes in temperature and radiative forcing must be derived from proxy data. It is also necessary to consider how different ice sheet and continental configurations acted as forcing,[254] as well as the temperature dependence of climate feedbacks.[255]

Synthesizing the implications for climate sensitivity from this extremely diverse body of evidence is nontrivial. Synthesis requires the development of a common framework to treat evidence based on extensions to the forcing–feedback paradigm,[2,21,256] as well as the sustained multiyear interaction of scientists from diverse research communities. Mathematical methods used in synthesis vary from complex Bayesian methods[21] to simpler consistency arguments.[2]

### Major Uncertainties and Research Gaps

A major uncertainty in the estimate of climate sensitivity involves the pattern of sea surface temperature warming in the Pacific for the long-term forced response to $CO_2$ doubling.[21] Over the last several decades, the observed pattern of warming has featured smaller warming or even cooling in the East Pacific,

increasing the amounts of low clouds and sunlight reflected back to space and thereby reducing the warming of Earth. It is thought that this pattern in the recent past is due to natural climate variability. It is expected that over the 21st century, the warming in the East Pacific will catch up to and exceed that in the West Pacific, matching the predictions of CMIP models for $CO_2$-dominated warming. However, if the observed recent pattern of warming includes a component of the forced response to $CO_2$ that models fail to predict, then climate sensitivity values at the high end are less likely.

Other key climate sensitivity uncertainties[21] include 1) the scaling ratios between feedbacks estimated from the smaller short-term temperature variability and the larger climate change expected in the 21st century; 2) the cloud feedbacks from cloud types other than the well-studied marine low clouds; 3) the magnitude of aerosol forcing over the historical period, knowledge of which is critical for determining the component of historical warming from GHGs; 4) the abundance of dust and other aerosols in the Last Glacial Maximum; 5) the characterization by proxy records of temperature, trace gases, and other forcing agents for warm periods in the deep geological past; 6) the dependence of climate sensitivity on the background state; and 7) the accounting for Earth system effects when interpreting the consequences of the paleoclimate record for a climate sensitivity applicable to 21st-century warming.

### Description of Confidence and Likelihood

The *likely* ranges of climate sensitivity are derived from the synthesis of the evidence base through the framework of the forcing–feedback paradigm.[2,21,256] Confidence is *high* in the reduced range of climate sensitivity because its observational estimates are derived from three independent lines of evidence and because the three central estimates of climate sensitivity are in general agreement. The three lines of evidence are 1) evidence from natural climate variability in the present day, 2) evidence from the changes in climate from the preindustrial period to the present day, and 3) evidence from the changes in climate from various cold and warm periods in the paleoclimate record. Additional reasons for *high confidence* include a greater understanding of how physical climate feedbacks vary with the nature of changes for different timescales and a greater ability to synthesize diverse evidence from different periods in Earth's past.

## Key Message 3.3

## New Data and Analysis Methods Have Advanced Climate Science

### Description of Evidence Base

#### Advances in Earth System Observations

From temperature and precipitation observations that began in the 1800s through the earliest observations of $CO_2$ concentration taken on Mauna Loa from the late 1950s[257] and into the satellite era,[258] observations of the Earth system have been essential for constraining climate models and improving our understanding of the climate system. Since the last National Climate Assessment was released in 2018, several major advancements in understanding of the Earth system have arisen from observational platforms.

New observations using eddy covariance measurements from AmeriFlux and NEON and subsequent science are described in Novick et al. (2018)[259] and Chabbi and Loescher (2017),[260] respectively. A deeper understanding of the water cycle derived from subsurface and surface runoff from USGS is described in USGS (2019).[261] Improvements in estimating surface energy balance from ARM and other BSRN sites is described in Wild (2017).[262] Better constraints of uncertainty in near-surface temperatures from GISTEMP comes from Lenssen et al. (2019).[248] Understanding of atmospheric $CO_2$ and related gases comes from NOAA ESRL GML.[263] Understanding of ocean temperature, salinity, and key biogeochemical concentrations comes from buoys, ship tracks, floats, drifters,[264,265] and Saildrones.

Observational evidence to constrain Earth's heating rate from CERES and AIRS is described in Loeb et al. (2021)[266] and Susskind et al. (2019),[267] respectively. Improved evidence of sea level rise using satellite altimetry is documented in Li et al. (2022)[268] and Nerem et al. (2018).[162] Recently deployed NASA and NOAA satellite observing systems are documented in Fisher et al. (2020;[269] ECOSTRESS), Dubayah et al. (2020;[270] GEDI), Green et al. (2020;[271] EMIT), Zavodsky et al. (2017;[272] TROPICS), Goldberg and Zhou (2017;[273] JPSS-2), and Morrow et al. (2019;[274] SWOT). NASA JPL's ASO is described in Painter et al. (2016).[275] The USGS NGWOS system is described in Eberts et al. (2019).[276]

### New Scenarios and Climate Projections

The development of the set of new scenarios used by CMIP6 by the so-called parallel process[277] started while the CMIP5 simulations based on the Representative Concentration Pathways (RCPs) were produced, analyzed, and assessed in IPCC 2013[278] (the stage-setting essay for the new scenarios development is Ebi et al. 2014[279]). The new scenarios are based on plausible future alternative pathways of socioeconomic development (the Shared Socioeconomic Pathways [SSPs]) from which consistent GHG emissions trajectories unfold, as opposed to simply consisting of idealized trajectories of future GHGs. Idealized trajectories (like a 1% annual increase in $CO_2$ concentrations or an instantaneous doubling of $CO_2$ concentrations) are useful sensitivity experiments, but they cannot be considered plausible, being decoupled from assumptions about human-caused emissions. About 40 modeling centers from all over the world participated in CMIP6 and ScenarioMIP.[280]

### Large Ensemble Simulations

About a decade ago, the first initial-condition ("large") ensembles were created (e.g., Deser et al. 2012,[281] 2012[282]) with a single model, followed by other models[283] and large ensembles with up to 100 simulations.[284] Currently there are large ensembles from many other climate models,[53] and the model intercomparison protocol for the most recent generation of simulations encouraged large ensembles of 10 realizations for all models.[30]

Large ensembles are used to estimate uncertainty from natural variability separately from the model uncertainty among climate models.[86] They have revealed the dependence of some aspects of natural variability, like precipitation, on climate state.[110] Large ensembles have also enabled the isolation of the response to different climate forcings, independent of natural variability and assessment of the linearity of these responses[53] or lack thereof.[285] They have also been used to assess whether El Niño–Southern Oscillation (ENSO) events and their impacts on precipitation and temperature over North America will change in the future[286,287,288] and to assess how large-scale atmospheric circulation patterns that affect US weather and climate may be altered by the effects of climate change.[289] Emerging applications of large ensembles include addressing questions related to the timing of when human-induced climate change signals exceed the natural variability of the climate,[290] risk assessment,[291] US water resources,[292] air pollution and associated health impacts,[293,294] and ecosystem stressors[295] (see Deser et al. 2020[53] for other examples).

### Emergent Constraints

Emergent constraints have been widely applied to reduce the simulated spread in the climate feedbacks that shape climate sensitivity.[240,246,247] Emergent constraints have also been applied to many other climate processes (see Hall et al. 2019[55] for a list). Williamson et al. (2021)[296] also provide a recent and comprehensive review of the emergent constraint literature and identify the various uncertainties in the physical and biogeochemical system responses that have been reduced in a credible way through the emergent constraint technique.

### Extreme Event Attribution

Since the landmark study of Stott et al. (2004),[72] which concluded that the chances of the 2003 European heatwave doubled due to anthropogenic climate change, many different author teams have analyzed a wide variety of extreme weather events to identify if there was a human influence. This large body of literature has been developed using many different approaches that have been surveyed by the author team. Of particular interest are a series of special supplements published since 2011 in the *Bulletin of the American Meteorological Society*.[60,61,62,297,298,299,300,301,302,303] Chapter authors have contributed to these reports and have published event attribution studies in the general literature.

Confidence in attributing the human influence, if any, on individual extreme weather events is increased when multiple independent author teams arrive at similar conclusions using different methods, observational estimates, and models, coupled with a thorough understanding of the physical processes of change. The copious amount of precipitation experienced in the greater Houston area during Hurricane Harvey provides a case in point, where three different teams concluded that anthropogenic climate change led to large attributable increases in storm total rainfall.[82,83,84] Confidence in this attribution has been further increased by the subsequent studies of other hurricanes, leading to similar conclusions.[63,78,192,304]

Confidence in an extreme event attribution statement hinges on reliable long-term observations.[66] Fortunately, much of the contiguous US (CONUS) is well observed since 1950 by the NOAA Global Historical Climate Network weather station measurements of temperature and precipitation. In many locations, reliable records span an entire century.[305]

Attribution is an exercise in causal inference; climate change attribution studies borrow techniques from the well-established epidemiology literature. Typical Pearl causal inference experiments involve two groups, a controlled (or placebo) group and a tested group.[306] As there is only one Earth, climate change attribution experiments can be performed only with numerical models. The limitations of climate models impose important caveats on any resulting attribution statements. The CMIP database of global climate models (GCMs) has been extensively used in attribution statements.[307,308] However, it is best suited for extreme events of larger spatial scales matching that of the CMIP models (e.g., heatwaves). More customized numerical experiments at higher resolution may be required for more localized extremes such as intense storms (including hurricanes).[64] Granger causal inference has also been applied to long observational records to make attribution statements without using climate models.[67,309] While a weaker form of causal inference due to the possibility of hidden covariates in the underlying statistical models (i.e., statistical model construction may bias findings), Granger causal inference can add to our understanding of changes in extreme event frequency and magnitude.

## Major Uncertainties and Research Gaps

### Advances in Earth System Observations

Unfortunately, not all quantities relevant to the Earth system can be easily observed. Although recent satellite missions such as GRACE[310] have been able to use gravitational measurements to constrain subsurface moisture, much of the subsurface remains poorly understood. Ongoing work has also suggested that deep-ocean heat content may have been underestimated,[311] a consequence of insufficient measurements of the deep ocean. Further, in situ measurements are generally more available within developed countries and in more easily accessed regions, resulting in significant observational gaps in the Southern Hemisphere (e.g., Guo et al. 2009[312]) and at high elevation.[313,314]

### New Scenarios and Climate Projections

Scenarios of future emissions and land-use change are developed as plausible alternatives, but no relative likelihood is attached to them. Some recent studies, however, have argued that the highest scenario,

SSP5-8.5, is no longer plausible without a reversal of current trends in the adoption of renewables and energy efficiency. The scenario development community is always testing the structural uncertainties of integrated assessment models and, therefore, the assumptions that produce the alternative emissions pathways. Timely updates of the baseline from which future projections are made, on the basis of current trends and observations of emissions, are necessary to maintain the plausibility of alternative pathways.

### Large Ensemble Simulations

Much remains to be done to obtain decision-relevant information at the scale of impacts—regional to local—with quantified uncertainty grounded in understanding of the natural variability, forcing, and structural sources of uncertainty. Identifying the forced pattern of response on local scales and separating it from natural variability is a continuing challenge, which has immediate implications for predictability, climate model evaluation, and the potential to narrow uncertainty in climate projections. Another key challenge is the so-called signal-to-noise paradox, which implies that models underestimate atmospheric predictability due to incomplete representations of key atmospheric and oceanic processes.[315] Thus, as models improve, there may be the potential to deliver more skillful climate predictions. Stakeholder and decision-maker input on what uncertainty is tolerable for specific applications, and what this means for the size of large ensembles, is another outstanding topic. The role of natural variability for many impacts, including air quality, has yet to be fully addressed. Finally, the implications of potential changes in natural variability for decadal prediction and predictability are still open questions. For example, what is the timescale of predictability? How predictable is *x* variable on *y* timescale?

### Emergent Constraints

Both Williamson et al. (2021)[296] and Hall et al. (2019)[55] identify major research gaps and uncertainties associated with the emergent constraint technique. Uncertainties include the following: 1) some proposed emergent constraints lack of out-of-sample testing in other model ensembles, 2) some proposed emergent constraints are characterized by a strong statistical relationship but lack a physical or theoretical framework to support the emergent relationship, and 3) some proposed emergent constraints lack observational data to constrain the future response, even assuming the emergent relationship is statistically robust and supported by a physical mechanism or theory. In addition, most emergent constraints have been applied to quantities of relevance to the global climate system. Going forward, it would be helpful to have more emergent constraints developed at the regional scale to reduce uncertainty in quantities of greatest relevance to the US or other regions.

### Extreme Event Attribution

Confidence in extreme attribution statement depends on both our understanding of the underlying physical mechanisms of change as well as on the fitness of our statistical and climate models.[65] This, of course, varies significantly depending on the nature of the extreme weather event. Attribution statements about the human influence on severe heatwaves and cold snaps are generally considered to be most confident.[221] Confidence in attribution statements about extreme precipitation vary greatly depending on storm type. Hurricane precipitation has been among the most-studied event, and recent assessment has concluded that modeling and satellite studies, as well as physical understanding, provide strong evidence that hurricane rainfall rates increased and will continue to increase due to anthropogenic climate change.[221,316] The Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6 WGI) concluded that "event attribution studies and physical understanding indicate that human-induced climate change increases heavy precipitation associated with tropical cyclones (*high confidence*), but data limitations inhibit clear detection of past trends on the global scale."[20] Partly based on CMIP5 models, the World Meteorological Organization's Tropical Cyclone Expert Team[42] concluded: "For TC precipitation rates, there is at least medium-to-high confidence in an increase globally, with a median projected increase of 14%, or close to the rate of tropical water vapor increase with warming, at constant

relative humidity." However recent higher-resolution modeling studies, particularly event attribution studies, find that hurricane precipitation increases at a rate substantially higher than that of water vapor alone, implying dynamical as well as thermodynamical changes (e.g., Reed et al. 2021,[304] 2022;[63] Risser and Wehner 2017;[82] van Oldenborgh et al. 2017;[83] Wang et al. 2018[84]). A recent satellite-based study reinforces this interpretation.[316] Atmospheric rivers and extratropical cyclones have received less attention, but it is expected that similar conclusions will be drawn as more studies are performed. Mesoscale convective systems (e.g., storms producing hail, tornadoes, and ice) are not so well studied due to both modeling and observational limitations of these specific local-scale events.

Changes in extreme wind events, such as produced by hurricanes, derechos, or Santa Ana–type events, are also poorly understood due to model limitations in realistically simulating these phenomena.

Extreme weather changes attributable to local thermodynamic processes are better understood than those due to changes in large-scale meteorological patterns due to uncertainty in changes in circulation patterns. Thus, attributable changes in meteorological drought (defined by rainfall deficits) caused by changing rainfall patterns from circulation are less well understood, especially for CONUS, than are attributable changes in agricultural and ecological drought (defined by increases in soil moisture deficit caused by warmer temperatures).[196]

Some events are so extreme that our statistical and climate models may not be fit for the purpose of quantifying the human influence, even if our understanding is such that we are confident that there is one. The 2021 heatwave in the Pacific Northwest is a good example. Temperatures experienced during this very rare compound extreme event are outside of the bounds of the fitted generalized extreme value statistical distributions typically used to ascertain changes in event frequency and magnitude. Also, it is unclear whether the standard ensemble of CMIP models can produce the specific large-scale meteorological patterns responsible for these record-breaking temperatures. For these very rare events, the recent development of large ensembles of climate models can increase our confidence in quantitative attribution statements in some instances.[53]

### Description of Confidence and Likelihood

The section is a description of factual results, so confidence and likelihood do not apply.

## Key Message 3.4

## Humans Are Changing Earth System Processes

### Description of Evidence Base

**Natural Variability**

In the last decade, there has been increasing recognition of the role of regional-scale natural variability in the past and future evolution of climate, as well as the fact that regional natural variability signals can be competitive with forced anthropogenic signals (e.g., Deser 2020[317]). The mechanisms by which the climate system generates such large levels of natural variability are well documented and understood. Examples of such modes of variability relevant to North American climate include ENSO, the Pacific Decadal Oscillation, the Pacific North American pattern, and the northern annular mode. Many of these patterns have limited predictability beyond a timescale of about two weeks, leading to an irreducible uncertainty in the actual evolution of climate. A caveat here relates to the ENSO phenomenon, which has some seasonal to interannual predictability. We also note that modes of variability themselves can also be affected by anthropogenic forcing, and these signals may be predictable.[318] This idea of irreducible uncertainty applies to

future projections only. It is not meant to cast doubt on anthropogenic climate change that has already been detected in the observational record despite natural variability.[221,235]

### Atmospheric Circulation Changes

Many aspects of atmospheric circulation changes have been studied using observations (global reanalysis) and model simulations. Important large-scale circulation features that influence US regional climate include the jet stream, storm tracks, the Aleutian low, the North Pacific and North Atlantic subtropical highs, North American Monsoon circulation, and others, which are strongly influenced by the overturning Hadley circulation in the tropics. In turn, large-scale circulation, such as the North Atlantic subtropical high, influences mesoscale circulation features, such as the Great Plains low-level jet that affects precipitation in the central and midwestern US. Hence, understanding how the Hadley circulation changes with warming is important for understanding changes in large-scale and mesoscale circulations affecting US regional climate. Staten et al. (2018)[89] and Grise et al. (2019)[90] synthesized previous studies documenting the poleward shift in the subsiding branches of the Hadley circulation since 1979. Both studies found that methodological differences in how the Hadley circulation is calculated can partly explain the discrepancy between the rate of tropical expansion derived from global reanalyses and model historical simulations found in previous studies. However, both studies also highlighted the challenge in detecting changes in the tropical expansion and attributing them to anthropogenic warming because of the large natural variability, particularly for the poleward expansion in the Northern Hemisphere that is more relevant to large-scale circulations affecting North America.

Besides the tropical expansion, many studies analyzed model simulations and projections of changes in large-scale circulations—such as the jet stream,[87,93,95,319] storm tracks,[320] extratropical cyclones,[189,321] and the North Atlantic subtropical high,[100,322]—and compared observed and model-simulated historical trends in sea level pressure.[323] Many of these studies used multimodel and large ensemble simulations to first determine if a robust signal of change is found and, if so, the mechanisms for how warming may influence the circulation features; the impacts of the circulation changes to precipitation are also often investigated. Model experiments allowing isolation of the direct radiative effect of $CO_2$, which is a fast process, versus the effect of sea surface temperature warming, which is a slower process, have also contributed to improving understanding of how increasing GHGs affect atmospheric circulation.

### Water Cycle Changes

A sizeable and expanding literature describes past and projected future changes in processes relevant to Earth's water cycle.[201,324] Much of the literature on the water cycle separates its projected past and future changes into two components: one proportional to the change in water vapor—the "thermodynamic" response—and another that depends on atmospheric circulation and other factors—the "dynamic" response. Water vapor changes increase at roughly constant relative humidity with warming,[325] with variations over land and during different phases of the response[326] that are relevant to the US. Changes in circulation also modulate the spatial pattern of extreme precipitation intensity change, increasing it in some regions and reducing it in others,[113] which is the main driver of the variations in magnitude and sign of precipitation change seasonally and regionally. Precipitation variability generally is projected to increase at all timescales and in most locations in response to GHG-driven warming.[110] This implies increases in both heavy precipitation extremes and drought,[111] a phenomenon called whiplash.[112]

### Changes in the Carbon and Biogeochemical Cycles

Observations show that about half of annually emitted $CO_2$ from human activities is absorbed by the terrestrial biosphere and oceans.[327] The observational record of atmospheric $CO_2$ growth and estimates of fossil fuel emissions based on economic fuel statistics are used to estimate the residual total uptake of carbon by the terrestrial ecosystem and the ocean. Determining the amount of uptake for land and oceans

is more complicated and uncertain. For the oceans, upscaled global measurements of the partial pressure of $CO_2$ ($pCO_2$) in seawater and total carbon in organic and inorganic compounds dissolved in interior ocean waters are used to estimate current and cumulative carbon sinks (e.g., Rödenbeck et al. 2015;[328] Takahashi et al. 2009[329]).

On land, direct measurements of atmosphere–land biosphere fluxes are used to understand carbon sources and sinks and their variability on daily to interannual timescales.[330]

#### Changes in Ocean, Cryosphere, and Sea Level

Over the course of the 20th century, sea level rise occurring on global scales estimated from reconstruction created from tide-gauge records has been explained by the individual processes contributing to it.[158] These process contributions were estimated from a combination of direct observations and observation-driven reconstructions. Using modern observation systems, global sea level rise from satellite altimetry between 2002 and 2017 has been explained using the in situ measurements of the Argo profiling floats and the observations of water-mass change from the GRACE and GRACE-FO satellites,[331] demonstrating closure of the global sea level budget. As seen in both tide-gauge and satellite records, the rate of global mean sea level rise has been increasing, driven by accelerating contributions from the underlying processes.[158,161,162]

At the regional level, similar studies have assessed the rates of sea level rise and performed similar budget studies as those conducted on global scales. The combination of models, reconstructions, and observations allows for accounting of all the relevant processes, and an understanding of the drivers of total sea level rise has been demonstrated on regional scales across a range of different timescales in several studies (e.g., Frederikse et al. 2017;[332] Harvey et al. 2021;[333] Rietbroek et al. 2016;[334] Walker et al. 2021[160]). The current relative sea level observation network measures the dominant processes contributing to regional sea level, and this has supported more dedicated, process-level studies on sea level rise.

#### Regional-Scale Changes

It has been well established since the earliest climate change assessments (e.g., IPCC 1990;[335] National Research Council 1979[336]) that the local climate change response in a particular variable can differ substantially from the corresponding globally averaged response. For the latest versions of the geographical distributions of the response in particular variables to anthropogenic forcing, and the corresponding globally averaged response, the reader is referred to examples seen in Figures SPM.5, SPM.8, TS.6 of the IPCC AR6 WGI.[13,20]

## Major Uncertainties and Research Gaps

#### Natural Variability

Because of the limited duration of the observational record, the magnitude of natural variability on decadal timescales and longer is not as well quantified as shorter-timescale variability. For example, the true natural variability of the climate system on decadal to centennial timescales could be larger than what we estimate from GCMs, which would further increase the irreducible uncertainty stemming from natural variability.

#### Atmospheric Circulation Changes

While advances have been made in reconciling the previously reported differences in tropical expansion rates in observations and model simulations, uncertainties remain, especially in future projections of tropical expansion in the Northern Hemisphere because of the large natural variability and the relatively small poleward expansion in response to increasing GHGs.[90] Some studies also highlighted several important sources of uncertainty in projecting midlatitude atmospheric circulation changes related to model biases (e.g., Dong et al. 2021[58]), a tug-of-war between opposing mechanisms (e.g., Shaw and Voigt 2015[319]), and natural variability (e.g., Deser et al. 2020;[53] Dong et al. 2021[87]). For historical century-scale

regional trends in sea level pressure, large differences were found between different observational estimates from gridded datasets and reanalysis reconstructions.[323]

As discussed in KM 3.4, large-scale circulation changes are influenced by meridional and vertical temperature gradients; thus, Arctic amplification (the enhancement of near-surface air temperature change over the Arctic relative to lower latitudes), besides changes in the tropical Hadley circulation, may also influence midlatitude atmospheric circulations such as blocking, with potential implications for cold extremes. However, significant challenges remain in connecting Arctic amplification to midlatitude circulation changes due to the complex nonlinear dynamics of the jet stream.[337,338]

#### Water Cycle Changes

Of note is the role of climate variability in many aspects of the water cycle (especially for changes at the regional scale): natural variability is known (with *high confidence*, from observations, theory, and simulations) to be large for many aspects of the water cycle, and this can result in a low ceiling to the likelihood that can be placed on any specific realization of the future or past water cycle, even in situations where confidence in understanding is high (see above, "Large Ensemble Simulations" in KM 3.3, and Douville et al. 2021[201]). For this reason, it is particularly important for the water cycle to focus on the probability of what could happen in the future and the probability that observed changes that have already occurred are due to forced changes (as opposed to natural variability), rather than focusing on specific deterministic trajectories of what has already happened or will happen in the future. Furthermore, forced changes in variability that are expected for precipitation and other aspects of the water cycle complicate this picture further, more than for other variables such as temperature.

For extreme precipitation in particular, an outstanding question is whether, and if so how much, the thermodynamic and dynamic components of extreme precipitation change are coupled.[339] This would imply a positive feedback mechanism that could amplify extreme precipitation increases beyond the thermodynamic increase.

One uncertainty is the role of vegetation in modulating changes in evapotranspiration, which can in turn influence other factors including soil moisture, streamflow, and wildfire. In addition to changing evaporation from soil, plants also influence total evaporation through competing effects. In response to increased atmospheric $CO_2$ concentrations, plant stomata do not need to open as much to take in $CO_2$ for photosynthesis, which can reduce the amount of water they lose through transpiration, thus decreasing total evapotranspiration.[340] Conversely, an overall increase in the amount of vegetation can amplify evaporative losses and surface drying.[215,341,342] It is not yet clear which of these mechanisms will predominate, although model projections and observational analyses for the US suggest that the net effect will be for warming to increase evaporation and surface drying in much of the country.[199,200,207,208,343]

A key gap in understanding the hydrologic cycle and how it can change is the enormous range of scales in space and time on which relevant processes operate, from the scale of nanometers (cloud condensation nuclei), to the scale of cloud systems and watersheds (1 km to 1,000s of km), to the whole globe (evaporation and precipitation constitute a large fraction of energy flow between the surface and atmosphere). No observing system can capture, and no numerical model can represent, all of these processes at once, which is a key challenge for understanding and projecting the water cycle and its change. Continuing to increase the range of scales that can be captured by consistent, continuous observing systems and represented within a single model is one promising path toward decreasing some of the uncertainty in the future water cycle.[201]

### Changes in the Carbon and Biogeochemical Cycles

Carbon fluxes, especially from the terrestrial biosphere are spatially heterogeneous and can undergo large temporal changes as well. Observations used to estimate carbon fluxes are sparsely distributed, and data records are often too short to be used to characterize interannual variability and trends. Models of ocean circulation and biogeochemistry and detailed models of plant growth and dynamics can be used to upscale carbon fluxes using observations for guidance, but there is significant uncertainty in many processes, such as the effects of nutrient limitation on plants and phytoplankton and responses to climate changes. Machine learning approaches have also been used to upscale flux observations (e.g., Jung et al. 2020[344]). Inverse modeling combines information from atmospheric observations, atmospheric transport models, and best-available estimates of carbon fluxes from land and ocean via models to produce carbon flux estimates; however, these modeling systems are also limited by sparse data. Major regions that are important for understanding the global carbon budget, such as the tropics and Siberia, do not have adequate observational coverage, and this lack makes accurate estimates of land and ocean fluxes difficult to achieve.

All of the above-mentioned issues, and the large uncertainty associated with future emissions, make predicting the future evolution of the carbon cycle difficult. Uncertainties in future climate drivers such as temperature, precipitation, and cloudiness result in uncertainty in how land and ocean biogeochemistry will evolve in the future. Furthermore, the difficulties in modeling nutrient availability and limitation, as well as disturbances such as fires, insect and disease outbreaks, severe weather, and human land-use change, introduce more uncertainties that affect predictions of how the carbon cycle and climate change will interact. The mobilization to the atmosphere of $CO_2$ and $CH_4$ from enhanced decomposition of the huge reserves of carbon in Arctic soils represents a potentially important positive carbon cycle–climate feedback, but it is particularly difficult to model due to difficult-to-quantify processes like cryoturbation and local erosion and thermokarst processes.[345] Current carbon cycle models that are coupled to climate models disagree widely on the future response of carbon exchanges between the oceans, land biosphere, and atmosphere to continued fossil fuel emissions. The range of responses has not appreciably changed since the previous model intercomparison (CMIP5).[134]

### Changes in Ocean, Cryosphere, and Sea Level

Many of the components of the modern sea level observation network—particularly space-based platforms—are limited in their coverage of coastal regions. The US coastlines have better coverage from tide gauges than other parts of the world, although large gaps between tide gauges are still present. This is also true of measurements of coastal subsidence that generally originate from point-measurements from the Global Positioning System, although satellite-based interferometric synthetic aperture radar (InSAR) provides a possible solution (e.g., Shirzaei et al. 2021[346]). The connection between open-ocean sea level change and the sea level change experienced at the coast is still an active research area.

As a result of observations and improved modeling efforts, there is increased consensus regarding the behavior of many of the ice sheet processes. However, the future response of the ice sheets as the climate continues to warm, and of some of the associated processes, is still uncertain. It has been hypothesized that two possible processes in particular, known as the marine ice cliff instability[151,152] and the marine ice sheet instability,[153,155,156] could lead to rapid ice sheet loss over the course of several decades. The physical processes that would result in these instabilities and how they would progress once triggered remain uncertain. Resolving these uncertainties would require continued and additional observations of the ice sheets—and ocean and atmosphere that surround them. Additionally, advances in ice sheet modeling that potentially leverage these observations are a priority to narrow future estimates of ice mass loss.

### Regional-Scale Changes

Although the idea that the regional climate change response differs from the globally averaged response is not controversial, there remain major uncertainties in the magnitudes of climate change responses at any given location. This reflects large differences in local outcomes across the GCM projections, as well as large differences in the local response when those GCMs are downscaled to higher resolution.

### Description of Confidence and Likelihood

The section is a description of general results, so confidence and likelihood do not apply.

## Key Message 3.5

## Humans Are Changing Weather and Climate Extremes

### Description of Evidence Basis

The theoretical basis of changes in extreme temperature and precipitation are well established. As temperature increases, a shift in the distribution implies that high temperatures become more frequent. Extreme precipitation occurs in saturated atmospheres. The Clausius–Clapeyron relationship, identified in the 19th century—specifying that saturation-specific humidity increases by between 6% and 7% per one degree Celsius of warming at typical surface air temperatures—dictates that available moisture during extreme storms increases with warming. The efficiency with which different types of storms precipitate that available moisture varies, as does the response in precipitation efficiency to warming. Limited event attribution studies and other high-resolution modeling studies find that extreme precipitation can increase at a rate greater than that indicated by Clausius–Clapeyron.

The effect of warming on drought varies between drought definitions. Understanding of changes in meteorological drought is limited by understanding of the atmospheric circulation changes that affect storm track and frequency. On the other hand, changes in agricultural drought are sensitive to changes in evapotranspiration, which increases sharply with increased temperatures.[221]

### Major Uncertainties and Research Gaps

Land surface and vegetation processes have substantial impacts on climate extremes through the modulation of energy fluxes between the surface and atmosphere and surface water partitioning.[347] For example, dry surface conditions (e.g., a drought) and urbanization can both amplify heat extremes,[348,349] while wetter soils can increase the risk of precipitation events causing large floods.[350,351] However, few long-term data on these processes are available at large scales,[348] and their representation in climate models is often highly simplified.[352] Further, despite the fact that many extremes are strongly tied to atmospheric circulation anomalies (e.g., atmospheric ridge events), changes in these dynamics remain highly uncertain. While changes in sea ice and meridional temperature gradients may be linked to increases in the frequency and persistence of midlatitude circulation patterns associated with extreme events (e.g., Coumou et al. 2018[353]), studies suggest that these changes have not yet emerged from background natural variability.[354] Confidence in model-based assessments of changes in frequency or intensity of extreme events can be enhanced in cases where a detectable anthropogenic trend in an extreme, or closely related metric, has been found. However, this is not the case for some extreme event types, including those related to long-term changes in circulation.

The ensembles of tropical cyclone–permitting (~20 km) model simulations are small both in the number of realizations and of independent climate models, which limits understanding of tropical storm statistics. Even fewer long convection–permitting (<4 km) regional model simulations are available, limiting our understanding of how mesoscale convection systems and similar intense storms will respond to warming.

The effect of warming on the processes leading to rapid intensification is also poorly understood. While theory and high-resolution modeling find that winds in the most intense storms become stronger, detection and attribution of such changes has not yet been accomplished, as the most common metric—the Saffir–Simpson wind speed—is an instantaneous point-wise maximum and very noisy.

Finally, climate change may be moving us into an era of large or unprecedented extremes that fall far outside the range of historical variability, particularly regarding temperature (e.g., Overland 2021[355]). In such cases, many statistical approaches may be insufficient and make it difficult, with any confidence, to conduct detection and attribution analyses.[76]

## Description of Confidence Likelihood

Anthropogenic forcing has increased the frequency, duration, and intensity of extreme heat across most land areas (*high confidence*),[20,356] with some evidence that extreme cold events have also declined (*medium confidence*).[308] These changes are driven by average shifts in the temperature distributions toward warmer conditions that are significant and robust across most of the world.[180] Heavy precipitation events have increased in some regions (*high confidence*)[20] because of the strong dependence of the water-holding capacity of the atmosphere on temperatures (e.g., Kunkel et al. 2013[357]). Coastal flood risk has increased, and is projected to continue to increase, because of sea level rise (*high confidence*; e.g., Vousdoukas et al. 2018[358]). Notably, while the most extreme river floods are expected to increase in severity because of increases in heavy precipitation (*high confidence*), more general trends are mixed because flood risk also depends on policies and land surface processes.[201] Soil moisture droughts are also increasing in frequency and severity in many regions (*medium* to *high confidence*)[20] through the direct effects of warming on snow, evapotranspiration, and plant water use.[43,215,342] There is also *high confidence* that the intensity and frequency of precipitation droughts are increasing in Mediterranean-climate regions.[359,360,361,362] Climate change increases fuel flammability through higher temperatures and lower humidity and has increased the area burned by wildfires in western US (*high confidence*)[217,219] and Australia.[363] Despite these climate change–driven regional increases, however, global burn area has declined in recent years as a consequence of agricultural expansion and intensification, especially in savanna and grassland ecosystems.[364]

While tropical cyclones are the most studied extreme storm type with high-resolution (~25 km) global models, more such simulations are required to develop a theory about cyclogenesis and intensity changes with climate change. While attribution studies find that extreme precipitation over land in major tropical cyclones *very likely* scales with temperature increases at rates greater than the Clausius–Clapeyron rate, average total tropical storm precipitation scales at least at Clausius–Clapeyron rates,[42] but confidence is limited as there are limited high-resolution projections. It is also *likely* that precipitation increases over land will differ from those over oceans.

# References


1. Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens, and X.Y. Zhang, 2013: Ch. 7. Clouds and aerosols. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, 571–658. https://doi.org/10.1017/cbo9781107415324.016

2. Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: Ch. 7. The Earth's energy budget, climate feedbacks, and climate sensitivity. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 923–1054. https://doi.org/10.1017/9781009157896.009

3. Fahey, D.W., S. Doherty, K.A. Hibbard, A. Romanou, and P.C. Taylor, 2017: Ch. 2. Physical drivers of climate change. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 73–113. https://doi.org/10.7930/j0513wcr

4. Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Ch. 5. Global carbon and other biogeochemical cycles and feedbacks. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 673–816. https://doi.org/10.1017/9781009157896.007

5. Lan, X., S. Basu, S. Schwietzke, L.M.P. Bruhwiler, E.J. Dlugokencky, S.E. Michel, O.A. Sherwood, P.P. Tans, K. Thoning, G. Etiope, Q. Zhuang, L. Liu, Y. Oh, J.B. Miller, G. Pétron, B.H. Vaughn, and M. Crippa, 2021: Improved constraints on global methane emissions and sinks using $\delta^{13}C$-$CH_4$. *Global Biogeochemical Cycles*, **35** (6), e2021GB007000. https://doi.org/10.1029/2021gb007000

6. Schaefer, H., S.E.M. Fletcher, C. Veidt, K.R. Lassey, G.W. Brailsford, T.M. Bromley, E.J. Dlugokencky, S.E. Michel, J.B. Miller, I. Levin, D.C. Lowe, R.J. Martin, B.H. Vaughn, and J.W.C. White, 2016: A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by $^{13}CH_4$. *Science*, **352** (6281), 80–84. https://doi.org/10.1126/science.aad2705

7. Szopa, S., V. Naik, B. Adhikary, P. Artaxo, T. Berntsen, W.D. Collins, S. Fuzzi, L. Gallardo, A. Kiendler-Scharr, Z. Klimont, H. Liao, N. Unger, and P. Zanis, 2021: Ch. 6. Short-lived climate forcers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 817–922. https://doi.org/10.1017/9781009157896.008

8. Tian, H., R. Xu, J.G. Canadell, R.L. Thompson, W. Winiwarter, P. Suntharalingam, E.A. Davidson, P. Ciais, R.B. Jackson, G. Janssens-Maenhout, M.J. Prather, P. Regnier, N. Pan, S. Pan, G.P. Peters, H. Shi, F.N. Tubiello, S. Zaehle, F. Zhou, A. Arneth, G. Battaglia, S. Berthet, L. Bopp, A.F. Bouwman, E.T. Buitenhuis, J. Chang, M.P. Chipperfield, S.R.S. Dangal, E. Dlugokencky, J.W. Elkins, B.D. Eyre, B. Fu, B. Hall, A. Ito, F. Joos, P.B. Krummel, A. Landolfi, G.G. Laruelle, R. Lauerwald, W. Li, S. Lienert, T. Maavara, M. MacLeod, D.B. Millet, S. Olin, P.K. Patra, R.G. Prinn, P.A. Raymond, D.J. Ruiz, G.R. van der Werf, N. Vuichard, J. Wang, R.F. Weiss, K.C. Wells, C. Wilson, J. Yang, and Y. Yao, 2020: A comprehensive quantification of global nitrous oxide sources and sinks. *Nature*, **586** (7828), 248–256. https://doi.org/10.1038/s41586-020-2780-0

9. Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, 2007: Ch. 2. Changes in atmospheric constituents and in radiative forcing. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2.html

10. Gulev, S.K., P.W. Thorne, J. Ahn, F.J. Dentener, C.M. Domingues, S. Gerland, D. Gong, D.S. Kaufman, H.C. Nnamchi, J. Quaas, J.A. Rivera, S. Sathyendranath, S.L. Smith, B. Trewin, K. von Schuckmann, and R.S. Vose, 2021: Ch. 2. Changing state of the climate system. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 287–422. https://doi.org/10.1017/9781009157896.004

11. Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, 2013: Ch. 8. Anthropogenic and natural radiative forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 659–740. https://www.ipcc.ch/report/ar5/wg1/

12. Quaas, J., H. Jia, C. Smith, A.L. Albright, W. Aas, N. Bellouin, O. Boucher, M. Doutriaux-Boucher, P.M. Forster, D. Grosvenor, S. Jenkins, Z. Klimont, N.G. Loeb, X. Ma, V. Naik, F. Paulot, P. Stier, M. Wild, G. Myhre, and M. Schulz, 2022: Robust evidence for reversal of the trend in aerosol effective climate forcing. *Atmospheric Chemistry and Physics*, **22** (18), 12221–12239. https://doi.org/10.5194/acp-22-12221-2022

13. Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld, 2021: Technical summary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 33–144. https://doi.org/10.1017/9781009157896.002

14. Chen, L. and P.A. Dirmeyer, 2019: Global observed and modelled impacts of irrigation on surface temperature. *International Journal of Climatology*, **39** (5), 2587–2600. https://doi.org/10.1002/joc.5973

15. Bonan, G.B., 2008: Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, **320** (5882), 1444–1449. https://doi.org/10.1126/science.1155121

16. Prevedello, J.A., G.R. Winck, M.M. Weber, E. Nichols, and B. Sinervo, 2019: Impacts of forestation and deforestation on local temperature across the globe. *PLoS ONE*, **14** (3), e0213368. https://doi.org/10.1371/journal.pone.0213368

17. Friberg, J., B.G. Martinsson, M.K. Sporre, S.M. Andersson, C.A.M. Brenninkmeijer, M. Hermann, P.F.J. van Velthoven, and A. Zahn, 2015: Influence of volcanic eruptions on midlatitude upper tropospheric aerosol and consequences for cirrus clouds. *Earth and Space Science*, **2** (7), 285–300. https://doi.org/10.1002/2015ea000110

18. Schmidt, A., M.J. Mills, S. Ghan, J.M. Gregory, R.P. Allan, T. Andrews, C.G. Bardeen, A. Conley, P.M. Forster, A. Gettelman, R.W. Portmann, S. Solomon, and O.B. Toon, 2018: Volcanic radiative forcing from 1979 to 2015. *Journal of Geophysical Research: Atmospheres*, **123** (22), 12491–12508. https://doi.org/10.1029/2018jd028776

19. Zhu, J. and J.E. Penner, 2020: Radiative forcing of anthropogenic aerosols on cirrus clouds using a hybrid ice nucleation scheme. *Atmospheric Chemistry and Physics*, **20** (13), 7801–7827. https://doi.org/10.5194/acp-20-7801-2020

20. IPCC, 2021: Summary for policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–32. https://doi.org/10.1017/9781009157896.001

21. Sherwood, S.C., M.J. Webb, J.D. Annan, K.C. Armour, P.M. Forster, J.C. Hargreaves, G. Hegerl, S.A. Klein, K.D. Marvel, E.J. Rohling, M. Watanabe, T. Andrews, P. Braconnot, C.S. Bretherton, G.L. Foster, Z. Hausfather, A.S. von der Heydt, R. Knutti, T. Mauritsen, J.R. Norris, C. Proistosescu, M. Rugenstein, G.A. Schmidt, K.B. Tokarska, and M.D. Zelinka, 2020: An assessment of Earth's climate sensitivity using multiple lines of evidence. *Reviews of Geophysics*, **58** (4), e2019RG000678. https://doi.org/10.1029/2019rg000678

22. Mitchell, J.F.B., C.A. Senior, and W.J. Ingram, 1989: $CO_2$ and climate: A missing feedback? *Nature*, **341** (6238), 132–134. https://doi.org/10.1038/341132a0

23. Ceppi, P., D.T. McCoy, and D.L. Hartmann, 2016: Observational evidence for a negative shortwave cloud feedback in middle to high latitudes. *Geophysical Research Letters*, **43** (3), 1331–1339. https://doi.org/10.1002/2015gl067499

24. Terai, C.R., S.A. Klein, and M.D. Zelinka, 2016: Constraining the low-cloud optical depth feedback at middle and high latitudes using satellite observations. *Journal of Geophysical Research: Atmospheres*, **121** (16), 9696–9716. https://doi.org/10.1002/2016jd025233

25. Hausfather, Z., K. Marvel, G.A. Schmidt, J.W. Nielsen-Gammon, and M. Zelinka, 2022: Climate simulations: Recognize the 'hot model' problem. *Nature*, **605** (7908), 26–29. https://doi.org/10.1038/d41586-022-01192-2

26. Sun, Q., C. Miao, Q. Duan, H. Ashouri, S. Sorooshian, and K.-L. Hsu, 2018: A review of global precipitation data sets: Data sources, estimation, and intercomparisons. *Reviews of Geophysics*, **56** (1), 79–107. https://doi.org/10.1002/2017RG000574

27. Leung, L.R., W.R. Boos, J.L. Catto, C. A. DeMott, G.M. Martin, J.D. Neelin, T.A. O'Brien, S. Xie, Z. Feng, N.P. Klingaman, Y.-H. Kuo, R.W. Lee, C. Martinez-Villalobos, S. Vishnu, M.D.K. Priestley, C. Tao, and Y. Zhou, 2022: Exploratory precipitation metrics: Spatiotemporal characteristics, process-oriented, and phenomena-based. *Journal of Climate*, **35** (12), 3659–3686. https://doi.org/10.1175/jcli-d-21-0590.1

28. Maloney, E.D., A. Gettelman, Y. Ming, J.D. Neelin, D. Barrie, A. Mariotti, C.-C. Chen, D.R.B. Coleman, Y.-H. Kuo, B. Singh, H. Annamalai, A. Berg, J.F. Booth, S.J. Camargo, A. Dai, A. Gonzalez, J. Hafner, X. Jiang, X. Jing, D. Kim, A. Kumar, Y. Moon, C.M. Naud, A.H. Sobel, K. Suzuki, F. Wang, J. Wang, A.A. Wing, X. Xu, and M. Zhao, 2019: Process-oriented evaluation of climate and weather forecasting models. *Bulletin of the American Meteorological Society*, **100** (9), 1665–1686. https://doi.org/10.1175/bams-d-18-0042.1

29. Simpson, I.R., J. Bacmeister, R.B. Neale, C. Hannay, A. Gettelman, R.R. Garcia, P.H. Lauritzen, D.R. Marsh, M.J. Mills, B. Medeiros, and J.H. Richter, 2020: An evaluation of the large-scale atmospheric circulation and its variability in CESM2 and other CMIP models. *Journal of Geophysical Research: Atmospheres*, **125** (13), e2020JD032835. https://doi.org/10.1029/2020jd032835

30. O'Neill, B.C., C. Tebaldi, D.P. van Vuuren, V. Eyring, P. Friedlingstein, G. Hurtt, R. Knutti, E. Kriegler, J.F. Lamarque, J. Lowe, G.A. Meehl, R. Moss, K. Riahi, and B.M. Sanderson, 2016: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, **9** (9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

31. O'Neill, B.C., E. Kriegler, K. Riahi, K.L. Ebi, S. Hallegatte, T.R. Carter, R. Mathur, and D.P. van Vuuren, 2014: A new scenario framework for climate change research: The concept of Shared Socioeconomic Pathways. *Climatic Change*, **122** (3), 387–400. https://doi.org/10.1007/s10584-013-0905-2

32. Riahi, K., D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J.C. Cuaresma, S. Kc, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J.C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, and M. Tavoni, 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

33. van Vuuren, D.P., E. Kriegler, B.C. O'Neill, K.L. Ebi, K. Riahi, T.R. Carter, J. Edmonds, S. Hallegatte, T. Kram, R. Mathur, and H. Winkler, 2014: A new scenario framework for climate change research: Scenario matrix architecture. *Climatic Change*, **122** (3), 373–386. https://doi.org/10.1007/s10584-013-0906-1

34. Kriegler, E., J. Edmonds, S. Hallegatte, K.L. Ebi, T. Kram, K. Riahi, H. Winkler, and D.P. van Vuuren, 2014: A new scenario framework for climate change research: The concept of shared climate policy assumptions. *Climatic Change*, **122** (3), 401–414. https://doi.org/10.1007/s10584-013-0971-5

35. Eyring, V., S. Bony, G.A. Meehl, C.A. Senior, B. Stevens, R.J. Stouffer, and K.E. Taylor, 2016: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, **9** (5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

36. Haarsma, R.J., M.J. Roberts, P.L. Vidale, C.A. Senior, A. Bellucci, Q. Bao, P. Chang, S. Corti, N.S. Fučkar, V. Guemas, J. von Hardenberg, W. Hazeleger, C. Kodama, T. Koenigk, L.R. Leung, J. Lu, J.J. Luo, J. Mao, M.S. Mizielinski, R. Mizuta, P. Nobre, M. Satoh, E. Scoccimarro, T. Semmler, J. Small, and J.S. von Storch, 2016: High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6. *Geoscientific Model Development*, **9** (11), 4185–4208. https://doi.org/10.5194/gmd-9-4185-2016

37. Jiaxiang, G., M. Shoshiro, M.J. Roberts, R. Haarsma, D. Putrasahan, C.D. Roberts, E. Scoccimarro, L. Terray, B. Vannière, and P.L. Vidale, 2020: Influence of model resolution on bomb cyclones revealed by HighResMIP-PRIMAVERA simulations. *Environmental Research Letters*, **15** (8), 084001. https://doi.org/10.1088/1748-9326/ab88fa

38. Wehner, M., J. Lee, M. Risser, P. Ullrich, P. Gleckler, and W.D. Collins, 2021: Evaluation of extreme sub-daily precipitation in high-resolution global climate model simulations. *Philosophical Transactions of the Royal Society* A: *Mathematical, Physical and Engineering Sciences*, **379** (2195), 20190545. https://doi.org/10.1098/rsta.2019.0545

39. Roberts, M.J., J. Camp, J. Seddon, P.L. Vidale, K. Hodges, B. Vanniere, J. Mecking, R. Haarsma, A. Bellucci, E. Scoccimarro, L.-P. Caron, F. Chauvin, L. Terray, S. Valcke, M.-P. Moine, D. Putrasahan, C. Roberts, R. Senan, C. Zarzycki, and P. Ullrich, 2020: Impact of model resolution on tropical cyclone simulation using the HighResMIP–PRIMAVERA multimodel ensemble. *Journal of Climate*, **33** (7), 2557–2583. https://doi.org/10.1175/jcli-d-19-0639.1

40. Roberts, M.J., J. Camp, J. Seddon, P.L. Vidale, K. Hodges, B. Vannière, J. Mecking, R. Haarsma, A. Bellucci, E. Scoccimarro, L.-P. Caron, F. Chauvin, L. Terray, S. Valcke, M.-P. Moine, D. Putrasahan, C.D. Roberts, R. Senan, C. Zarzycki, P. Ullrich, Y. Yamada, R. Mizuta, C. Kodama, D. Fu, Q. Zhang, G. Danabasoglu, N. Rosenbloom, H. Wang, and L. Wu, 2020: Projected future changes in tropical cyclones using the CMIP6 HighResMIP multimodel ensemble. *Geophysical Research Letters*, **47** (14), e2020GL088662. https://doi.org/10.1029/2020gl088662

41. Wehner, M.F., K.A. Reed, B. Loring, D. Stone, and H. Krishnan, 2018: Changes in tropical cyclones under stabilized 1.5 and 2.0 °C global warming scenarios as simulated by the Community Atmospheric Model under the HAPPI protocols. *Earth System Dynamics*, **9** (1), 187–195. https://doi.org/10.5194/esd-9-187-2018

42. Knutson, T., S.J. Camargo, J.C.L. Chan, K. Emanuel, C.H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2020: Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, **101** (3), 303–322. https://doi.org/10.1175/bams-d-18-0194.1

43. Siirila-Woodburn, E.R., A.M. Rhoades, B.J. Hatchett, L.S. Huning, J. Szinai, C. Tague, P.S. Nico, D.R. Feldman, A.D. Jones, W.D. Collins, and L. Kaatz, 2021: A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment*, **2** (11), 800–819. https://doi.org/10.1038/s43017-021-00219-y

44. Albano, C.M., M.I. McCarthy, M.D. Dettinger, and S.A. McAfee, 2021: Techniques for constructing climate scenarios for stress test applications. *Climatic Change*, **164** (3), 33. https://doi.org/10.1007/s10584-021-02985-6

45. Shepherd, T.G., 2016: A common framework for approaches to extreme event attribution. *Current Climate Change Reports*, **2** (1), 28–38. https://doi.org/10.1007/s40641-016-0033-y

46. Shepherd, T.G., 2019: Storyline approach to the construction of regional climate change information. *Proceedings of the Royal Society* A: *Mathematical, Physical and Engineering Sciences*, **475** (2225), 20190013. https://doi.org/10.1098/rspa.2019.0013

47. Garrido-Perez, J.M., C. Ordóñez, D. Barriopedro, R. García-Herrera, J.L. Schnell, and D.E. Horton, 2022: A storyline view of the projected role of remote drivers on summer air stagnation in Europe and the United States. *Environmental Research Letters*, **17** (1), 014026. https://doi.org/10.1088/1748-9326/ac4290

48. Michaelis, A.C., A. Gershunov, A. Weyant, M.A. Fish, T. Shulgina, and F.M. Ralph, 2022: Atmospheric river precipitation enhanced by climate change: A case study of the storm that contributed to California's Oroville Dam crisis. *Earth's Future*, **10** (3), e2021EF002537. https://doi.org/10.1029/2021ef002537

49. Patricola, C.M., M.F. Wehner, E. Bercos-Hickey, F.V. Maciel, C. May, M. Mak, O. Yip, A.M. Roche, and S. Leal, 2022: Future changes in extreme precipitation over the San Francisco Bay Area: Dependence on atmospheric river and extratropical cyclone events. *Weather and Climate Extremes*, **36**, 100440. https://doi.org/10.1016/j.wace.2022.100440

50. Chen, X., L.R. Leung, Y. Gao, Y. Liu, and M. Wigmosta, 2023: Sharpening of cold-season storms over the western United States. *Nature Climate Change*, **13** (2), 167–173. https://doi.org/10.1038/s41558-022-01578-0

51. Gutmann, E.D., R.M. Rasmussen, C. Liu, K. Ikeda, C.L. Bruyere, J.M. Done, L. Garrè, P. Friis-Hansen, and V. Veldore, 2018: Changes in hurricanes from a 13-yr convection-permitting pseudo–Global warming simulation. *Journal of Climate*, **31** (9), 3643–3657. https://doi.org/10.1175/jcli-d-17-0391.1

52. Ullrich, P.A., Z. Xu, A.M. Rhoades, M.D. Dettinger, J.F. Mount, A.D. Jones, and P. Vahmani, 2018: California's drought of the future: A midcentury recreation of the exceptional conditions of 2012–2017. *Earth's Future*, **6** (11), 1568–1587. https://doi.org/10.1029/2018ef001007

53. Deser, C., F. Lehner, K.B. Rodgers, T. Ault, T.L. Delworth, P.N. DiNezio, A. Fiore, C. Frankignoul, J.C. Fyfe, D.E. Horton, J.E. Kay, R. Knutti, N.S. Lovenduski, J. Marotzke, K.A. McKinnon, S. Minobe, J. Randerson, J.A. Screen, I.R. Simpson, and M. Ting, 2020: Insights from Earth system model initial-condition large ensembles and future prospects. *Nature Climate Change*, **10** (4), 277–286. https://doi.org/10.1038/s41558-020-0731-2

54. Eyring, V., P.M. Cox, G.M. Flato, P.J. Gleckler, G. Abramowitz, P. Caldwell, W.D. Collins, B.K. Gier, A.D. Hall, F.M. Hoffman, G.C. Hurtt, A. Jahn, C.D. Jones, S.A. Klein, J.P. Krasting, L. Kwiatkowski, R. Lorenz, E. Maloney, G.A. Meehl, A.G. Pendergrass, R. Pincus, A.C. Ruane, J.L. Russell, B.M. Sanderson, B.D. Santer, S.C. Sherwood, I.R. Simpson, R.J. Stouffer, and M.S. Williamson, 2019: Taking climate model evaluation to the next level. *Nature Climate Change*, **9** (2), 102–110. https://doi.org/10.1038/s41558-018-0355-y

55. Hall, A., P. Cox, C. Huntingford, and S. Klein, 2019: Progressing emergent constraints on future climate change. *Nature Climate Change*, **9** (4), 269–278. https://doi.org/10.1038/s41558-019-0436-6

56. Lehner, F., A.W. Wood, J.A. Vano, D.M. Lawrence, M.P. Clark, and J.S. Mankin, 2019: The potential to reduce uncertainty in regional runoff projections from climate models. *Nature Climate Change*, **9** (12), 926–933. https://doi.org/10.1038/s41558-019-0639-x

57. Lin, Y., W. Dong, M. Zhang, Y. Xie, W. Xue, J. Huang, and Y. Luo, 2017: Causes of model dry and warm bias over central U.S. and impact on climate projections. *Nature Communications*, **8** (1), 881. https://doi.org/10.1038/s41467-017-01040-2

58. Dong, L., L.R. Leung, J. Lu, and F. Song, 2021: Double-ITCZ as an emergent constraint for future precipitation over Mediterranean climate regions in the north hemisphere. *Geophysical Research Letters*, **48** (3), e2020GL091569. https://doi.org/10.1029/2020gl091569

59. National Academies of Sciences, Engineering, and Medicine, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. National Academies Press, Washington, DC, 186 pp. https://doi.org/10.17226/21852

60. Herring, S.C., N. Christidis, A. Hoell, and P.A. Stott, 2022: Explaining extreme events of 2020 from a climate perspective. *Bulletin of the American Meteorological Society*, **103** (3), S1–S117. https://doi.org/10.1175/bams-explainingextremeevents2020.1

61. Herring, S.C., N. Christidis, A. Hoell, M.P. Hoerling, and P.A. Stott, 2019: Explaining extreme events of 2017 from a climate perspective. *Bulletin of the American Meteorological Society*, **100** (1), S1–S117. https://doi.org/10.1175/bams-explainingextremeevents2017.1

62. Herring, S.C., N. Christidis, A. Hoell, J.P. Kossin, C.J. Schreck, III, and P.A. Stott, 2018: Explaining extreme events of 2016 from a climate perspective. *Bulletin of the American Meteorological Society*, **99** (1), S1–S157. https://doi.org/10.1175/bams-explainingextremeevents2016.1

63. Reed, K.A., M.F. Wehner, and C.M. Zarzycki, 2022: Attribution of 2020 hurricane season extreme rainfall to human-induced climate change. *Nature Communications*, **13** (1), 1905. https://doi.org/10.1038/s41467-022-29379-1

64. Wehner, M.F., C. Zarzycki, and C. Patricola, 2019: Ch. 12. Estimating the human influence on tropical cyclone intensity as the climate changes. In: *Hurricane Risk*. Collins, J.M. and K. Walsh, Eds. Springer, Cham, Switzerland, 235–260. https://doi.org/10.1007/978-3-030-02402-4_12

65. Otto, F.E.L., L.J. Harrington, D. Frame, E. Boyd, K.C. Lauta, M. Wehner, B. Clarke, E. Raju, C. Boda, M. Hauser, R.A. James, and R.G. Jones, 2020: Toward an inventory of the impacts of human-induced climate change. *Bulletin of the American Meteorological Society*, **101** (11), E1972–E1979. https://doi.org/10.1175/bams-d-20-0027.1

66. Knutson, T., 2017: Detection and attribution methodologies overview. In: *Climate Science Special Report: Fourth National Climate Assessment*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 443–451. https://doi.org/10.7930/j0319t2j

67. Ebert-Uphoff, I. and Y. Deng, 2015: Ch. 11. Using causal discovery algorithms to learn about our planet's climate. In: *Machine Learning and Data Mining Approaches to Climate Science*. Lakshmanan, V., E. Gilleland, A. McGovern, and M. Tingley, Eds. Springer, Cham, Switzerland, 113–126. https://doi.org/10.1007/978-3-319-17220-0_11

68. Risser, M., W. Collin, M. Wehner, T. O'Brien, C. Paciorek, J.P. O'Brien, C. Patricola, H. Huang, P. Ullrich, and B. Loring, 2021: A method for detection and attribution of regional precipitation change using Granger causality application to the United States historical record. *Climate Dynamics*. https://doi.org/10.21203/rs.3.rs-785460/v1

69. Risser, M.D., W.D. Collins, M.F. Wehner, T.A. O'Brien, C.J. Paciorek, J.P. O'Brien, C.M. Patricola, H. Huang, P.A. Ullrich, and B. Loring, 2023: A framework for detection and attribution of regional precipitation change: Application to the United States historical record. *Climate Dynamics*, **60**, 705–741. https://doi.org/10.1007/s00382-022-06321-1

70. Perkins-Kirkpatrick, S.E., D.A. Stone, D.M. Mitchell, S. Rosier, A.D. King, Y.T.E. Lo, J. Pastor-Paz, D. Frame, and M. Wehner, 2022: On the attribution of the impacts of extreme weather events to anthropogenic climate change. *Environmental Research Letters*, **17** (2), 024009. https://doi.org/10.1088/1748-9326/ac44c8

71. van der Wiel, K., N. Wanders, F.M. Selten, and M.F.P. Bierkens, 2019: Added value of large ensemble simulations for assessing extreme river discharge in a 2 °C warmer world. *Geophysical Research Letters*, **46** (4), 2093–2102. https://doi.org/10.1029/2019gl081967

72. Stott, P.A., D.A. Stone, and M.R. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature*, **432** (7017), 610–614. https://doi.org/10.1038/nature03089

73. Kam, J., S.-K. Min, Y.-H. Kim, B.-H. Kim, and J.-S. Kug, 2022: Anthropogenic contribution to the record-breaking warm and wet winter 2019/20 over northwest Russia. *Bulletin of the American Meteorological Society*, **103** (3), S38–S43. https://doi.org/10.1175/bams-d-21-0148.1

74. Pall, P., C.M. Patricola, M.F. Wehner, D.A. Stone, C.J. Paciorek, and W.D. Collins, 2017: Diagnosing conditional anthropogenic contributions to heavy Colorado rainfall in September 2013. *Weather and Climate Extremes*, **17**, 1–6. https://doi.org/10.1016/j.wace.2017.03.004

75. Takayabu, I., K. Hibino, H. Sasaki, H. Shiogama, N. Mori, Y. Shibutani, and T. Takemi, 2015: Climate change effects on the worst-case storm surge: A case study of Typhoon Haiyan. *Environmental Research Letters*, **10** (6), 064011. https://doi.org/10.1088/1748-9326/10/6/064011

76. Philip, S.Y., S.F. Kew, G.J. van Oldenborgh, F.S. Anslow, S.I. Seneviratne, R. Vautard, D. Coumou, K.L. Ebi, J. Arrighi, R. Singh, M. van Aalst, C. Pereira Marghidan, M. Wehner, W. Yang, S. Li, D.L. Schumacher, M. Hauser, R. Bonnet, L.N. Luu, F. Lehner, N. Gillett, J. Tradowsky, G.A. Vecchi, C. Rodell, R.B. Stull, R. Howard, and F.E.L. Otto, 2021: Rapid attribution analysis of the extraordinary heat wave on the Pacific coast of the US and Canada in June 2021. *Earth System Dynamics*, **13** (4), 1689–1713. https://doi.org/10.5194/esd-13-1689-2022

77. van der Wiel, K., S.B. Kapnick, G.J. van Oldenborgh, K. Whan, S. Philip, G.A. Vecchi, R.K. Singh, J. Arrighi, and H. Cullen, 2017: Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. *Hydrology and Earth System Sciences*, **21** (2), 897–921. https://doi.org/10.5194/hess-21-897-2017

78. Reed, K.A., A.M. Stansfield, M.F. Wehner, and C.M. Zarzycki, 2020: Forecasted attribution of the human influence on Hurricane Florence. *Science Advances*, **6** (1), 9253. https://doi.org/10.1126/sciadv.aaw9253

79. Wehner, M.F. and K.A. Reed, 2022: Operational extreme weather event attribution can quantify climate change loss and damages. *PLoS Climate*, **1** (2), e0000013. https://doi.org/10.1371/journal.pclm.0000013

80. van Oldenborgh, G.J., K. van der Wiel, S. Kew, S. Philip, F. Otto, R. Vautard, A. King, F. Lott, J. Arrighi, R. Singh, and M. van Aalst, 2021: Pathways and pitfalls in extreme event attribution. *Climatic Change*, **166** (1), 13. https://doi.org/10.1007/s10584-021-03071-7

81. van Oldenborgh, G.J., M.F. Wehner, R. Vautard, F.E.L. Otto, S.I. Seneviratne, P.A. Stott, G.C. Hegerl, S.Y. Philip, and S.F. Kew, 2022: Attributing and projecting heatwaves is hard: We can do better. *Earth's Future*, **10** (6), e2021EF002271. https://doi.org/10.1029/2021ef002271

82. Risser, M.D. and M.F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophysical Research Letters*, **44** (24), 12457–12464. https://doi.org/10.1002/2017gl075888

83. van Oldenborgh, G.J., K. van der Wiel, A. Sebastian, R. Singh, J. Arrighi, F. Otto, K. Haustein, S. Li, G. Vecchi, and H. Cullen, 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12** (12), 124009. https://doi.org/10.1088/1748-9326/aa9ef2

84. Wang, S.Y.S., L. Zhao, J.-H. Yoon, P. Klotzbach, and R.R. Gillies, 2018: Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas. *Environmental Research Letters*, **13** (5), 054014. https://doi.org/10.1088/1748-9326/aabb85

85. Wehner, M. and C. Sampson, 2021: Attributable human-induced changes in the magnitude of flooding in the Houston, Texas region during Hurricane Harvey. *Climatic Change*, **166** (1), 1–13. https://doi.org/10.1007/s10584-021-03114-z

86. Lehner, F., C. Deser, N. Maher, J. Marotzke, E.M. Fischer, L. Brunner, R. Knutti, and E. Hawkins, 2020: Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. *Earth System Dynamics*, **11** (2), 491–508. https://doi.org/10.5194/esd-11-491-2020

87. Dong, L., L.R. Leung, F. Song, and J. Lu, 2021: Uncertainty in El Niño-like warming and California precipitation changes linked by the Interdecadal Pacific Oscillation. *Nature Communications*, **12** (1), 6484. https://doi.org/10.1038/s41467-021-26797-5

88. Perlwitz, J., T. Knutson, J.P. Kossin, and A.N. LeGrande, 2017: Ch. 5. Large-scale circulation and climate variability. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 161–184. https://doi.org/10.7930/j0rv0kvq

89. Staten, P.W., J. Lu, K.M. Grise, S.M. Davis, and T. Birner, 2018: Re-examining tropical expansion. *Nature Climate Change*, **8** (9), 768–775. https://doi.org/10.1038/s41558-018-0246-2

90. Grise, K.M., S.M. Davis, I.R. Simpson, D.W. Waugh, Q. Fu, R.J. Allen, K.H. Rosenlof, C.C. Ummenhofer, K.B. Karnauskas, A.C. Maycock, X.-W. Quan, T. Birner, and P.W. Staten, 2019: Recent tropical expansion: Natural variability or forced response? *Journal of Climate*, **32** (5), 1551–1571. https://doi.org/10.1175/jcli-d-18-0444.1

91. Simpson, I., 2018: Natural variability in the width of the tropics. *US CLIVAR Variations*, **16** (2), 14–20. https://usclivar.org/newsletters

92. Oudar, T., J. Cattiaux, and H. Douville, 2020: Drivers of the northern extratropical eddy-driven jet change in CMIP5 and CMIP6 models. *Geophysical Research Letters*, **47** (8), e2019GL086695. https://doi.org/10.1029/2019gl086695

93. Zhou, W., L.R. Leung, and J. Lu, 2022: Seasonally and regionally dependent shifts of the atmospheric westerly jets under global warming. *Journal of Climate*, **35** (16), 5433–5447. https://doi.org/10.1175/jcli-d-21-0723.1

94. Dong, L. and L.R. Leung, 2021: Winter precipitation changes in California under global warming: Contributions of $CO_2$, uniform SST warming, and SST change patterns. *Geophysical Research Letters*, **48** (5), e2020GL091736. https://doi.org/10.1029/2020gl091736

95. Neelin, J.D., B. Langenbrunner, J.E. Meyerson, A. Hall, and N. Berg, 2013: California winter precipitation change under global warming in the Coupled Model Intercomparison Project phase 5 ensemble. *Journal of Climate*, **26** (17), 6238–6256. https://doi.org/10.1175/jcli-d-12-00514.1

96. Zhou, W., L.R. Leung, and J. Lu, 2022: Seasonally dependent future changes in the U.S. Midwest hydroclimate and extremes. *Journal of Climate*, **35** (1), 17–27. https://doi.org/10.1175/jcli-d-21-0012.1

97. Song, F., L.R. Leung, J. Lu, and L. Dong, 2018: Future changes in seasonality of the North Pacific and North Atlantic subtropical highs. *Geophysical Research Letters*, **45** (21), 11959–11968. https://doi.org/10.1029/2018gl079940

98. Pascale, S., W.R. Boos, S. Bordoni, T.L. Delworth, S.B. Kapnick, H. Murakami, G.A. Vecchi, and W. Zhang, 2017: Weakening of the North American monsoon with global warming. *Nature Climate Change*, **7** (11), 806–812. https://doi.org/10.1038/nclimate3412

99. Cook, B.I. and R. Seager, 2013: The response of the North American Monsoon to increased greenhouse gas forcing. *Journal of Geophysical Research: Atmospheres*, **118** (4), 1690–1699. https://doi.org/10.1002/jgrd.50111

100. Song, F., L.R. Leung, J. Lu, and L. Dong, 2018: Seasonally dependent responses of subtropical highs and tropical rainfall to anthropogenic warming. *Nature Climate Change*, **8** (9), 787–792. https://doi.org/10.1038/s41558-018-0244-4

101. Song, F., L.R. Leung, J. Lu, L. Dong, W. Zhou, B. Harrop, and Y. Qian, 2021: Emergence of seasonal delay of tropical rainfall during 1979–2019. *Nature Climate Change*, **11** (7), 605–612. https://doi.org/10.1038/s41558-021-01066-x

102. Davini, P. and F. D'Andrea, 2020: From CMIP3 to CMIP6: Northern Hemisphere atmospheric blocking simulation in present and future climate. *Journal of Climate*, **33** (23), 10021–10038. https://doi.org/10.1175/jcli-d-19-0862.1

103. Neelin, J.D., S. Sahany, S.N. Stechmann, and D.N. Bernstein, 2017: Global warming precipitation accumulation increases above the current-climate cutoff scale. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (6), 1258–1263. https://doi.org/10.1073/pnas.1615333114

104. Groisman, P.Y., R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl, and V.N. Razuvaev, 2005: Trends in intense precipitation in the climate record. *Journal of Climate*, **18** (9), 1326–1350. https://doi.org/10.1175/jcli3339.1

105. Karl, T.R. and R.W. Knight, 1998: Secular trends of precipitation amount, frequency, and intensity in the United States. *Bulletin of the American Meteorological Society*, **79** (2), 231–241. DOI:10.1175/1520-0477(1998)079<0231:STOPAF>2.0.CO;2. https://journals.ametsoc.org/view/journals/bams/79/2/1520-0477_1998_079_0231_stopaf_2_0_co_2.xml

106. Pendergrass, A.G. and R. Knutti, 2018: The uneven nature of daily precipitation and its change. *Geophysical Research Letters*, **45** (21), 11980–11988. https://doi.org/10.1029/2018gl080298

107. Semenov, V. and L. Bengtsson, 2002: Secular trends in daily precipitation characteristics: Greenhouse gas simulation with a coupled AOGCM. *Climate Dynamics*, **19** (2), 123–140. https://doi.org/10.1007/s00382-001-0218-4

108. Pascale, S., S.B. Kapnick, S. Bordoni, and T.L. Delworth, 2018: The influence of $CO_2$ forcing on North American monsoon moisture surges. *Journal of Climate*, **31** (19), 7949–7968. https://doi.org/10.1175/jcli-d-18-0007.1

109. Polade, S.D., A. Gershunov, D.R. Cayan, M.D. Dettinger, and D.W. Pierce, 2017: Precipitation in a warming world: Assessing projected hydro-climate changes in California and other Mediterranean climate regions. *Scientific Reports*, **7** (1), 10783. https://doi.org/10.1038/s41598-017-11285-y

110. Pendergrass, A.G., R. Knutti, F. Lehner, C. Deser, and B.M. Sanderson, 2017: Precipitation variability increases in a warmer climate. *Scientific Reports*, **7** (1), 17966. https://doi.org/10.1038/s41598-017-17966-y

111. Ukkola, A.M., M.G. De Kauwe, M.L. Roderick, G. Abramowitz, and A.J. Pitman, 2020: Robust future changes in meteorological drought in CMIP6 projections despite uncertainty in precipitation. *Geophysical Research Letters*, **47** (11), e2020GL087820. https://doi.org/10.1029/2020gl087820

112. Swain, D.L., B. Langenbrunner, J.D. Neelin, and A. Hall, 2018: Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change*, **8** (5), 427–433. https://doi.org/10.1038/s41558-018-0140-y

113. Pfahl, S., P.A. O'Gorman, and E.M. Fischer, 2017: Understanding the regional pattern of projected future changes in extreme precipitation. *Nature Climate Change*, **7** (6), 423–427. https://doi.org/10.1038/nclimate3287

114. Gertler, C.G. and P.A. O'Gorman, 2019: Changing available energy for extratropical cyclones and associated convection in Northern Hemisphere summer. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (10), 4105–4110. https://doi.org/10.1073/pnas.1812312116

115. Fischer, E.M. and R. Knutti, 2016: Observed heavy precipitation increase confirms theory and early models. *Nature Climate Change*, **6** (11), 986–991. https://doi.org/10.1038/nclimate3110

116. Dong, L., L.R. Leung, J. Lu, and F. Song, 2019: Mechanisms for an amplified precipitation seasonal cycle in the U.S. West Coast under global warming. *Journal of Climate*, **32** (15), 4681–4698. https://doi.org/10.1175/jcli-d-19-0093.1

117. Luković, J., J.C.H. Chiang, D. Blagojević, and A. Sekulić, 2021: A later onset of the rainy season in California. *Geophysical Research Letters*, **48** (4), e2020GL090350. https://doi.org/10.1029/2020gl090350

118. Mote, P.W., S. Li, D.P. Lettenmaier, M. Xiao, and R. Engel, 2018: Dramatic declines in snowpack in the western US. *Npj Climate and Atmospheric Science*, **1** (1), 1–6. https://doi.org/10.1038/s41612-018-0012-1

119. Marshall, A.M., J.T. Abatzoglou, T.E. Link, and C.J. Tennant, 2019: Projected changes in interannual variability of peak snowpack amount and timing in the western United States. *Geophysical Research Letters*, **46** (15), 8882–8892. https://doi.org/10.1029/2019gl083770

120. Lehner, F., E.R. Wahl, A.W. Wood, D.B. Blatchford, and D. Llewellyn, 2017: Assessing recent declines in Upper Rio Grande runoff efficiency from a paleoclimate perspective. *Geophysical Research Letters*, **44** (9), 4124–4133. https://doi.org/10.1002/2017gl073253

121. Milly, P.C.D. and K.A. Dunne, 2020: Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. *Science*, **367** (6483), 1252–1255. https://doi.org/10.1126/science.aay9187

122. Woodhouse, C.A., G.T. Pederson, K. Morino, S.A. McAfee, and G.J. McCabe, 2016: Increasing influence of air temperature on upper Colorado River streamflow. *Geophysical Research Letters*, **43** (5), 2174–2181. https://doi.org/10.1002/2015gl067613

123. Friedlingstein, P., M.W. Jones, M. O'Sullivan, R.M. Andrew, D.C.E. Bakker, J. Hauck, C. Le Quéré, G.P. Peters, W. Peters, J. Pongratz, S. Sitch, J.G. Canadell, P. Ciais, R.B. Jackson, S.R. Alin, P. Anthoni, N.R. Bates, M. Becker, N. Bellouin, L. Bopp, T.T.T. Chau, F. Chevallier, L.P. Chini, M. Cronin, K.I. Currie, B. Decharme, L.M. Djeutchouang, X. Dou, W. Evans, R.A. Feely, L. Feng, T. Gasser, D. Gilfillan, T. Gkritzalis, G. Grassi, L. Gregor, N. Gruber, Ö. Gürses, I. Harris, R.A. Houghton, G.C. Hurtt, Y. Iida, T. Ilyina, I.T. Luijkx, A. Jain, S.D. Jones, E. Kato, D. Kennedy, K. Klein Goldewijk, J. Knauer, J.I. Korsbakken, A. Körtzinger, P. Landschützer, S.K. Lauvset, N. Lefèvre, S. Lienert, J. Liu, G. Marland, P.C. McGuire, J.R. Melton, D.R. Munro, J.E.M.S. Nabel, S.I. Nakaoka, Y. Niwa, T. Ono, D. Pierrot, B. Poulter, G. Rehder, L. Resplandy, E. Robertson, C. Rödenbeck, T.M. Rosan, J. Schwinger, C. Schwingshackl, R. Séférian, A.J. Sutton, C. Sweeney, T. Tanhua, P.P. Tans, H. Tian, B. Tilbrook, F. Tubiello, G.R. van der Werf, N. Vuichard, C. Wada, R. Wanninkhof, A.J. Watson, D. Willis, A.J. Wiltshire, W. Yuan, C. Yue, X. Yue, S. Zaehle, and J. Zeng, 2022: Global carbon budget 2021. *Earth System Science Data*, **14** (4), 1917–2005. https://doi.org/10.5194/essd-14-1917-2022

124. Chen, C., W.J. Riley, I.C. Prentice, and T.F. Keenan, 2022: $CO_2$ fertilization of terrestrial photosynthesis inferred from site to global scales. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (10), e2115627119. https://doi.org/10.1073/pnas.2115627119

125. Pugh, T.A.M., M. Lindeskog, B. Smith, B. Poulter, A. Arneth, V. Haverd, and L. Calle, 2019: Role of forest regrowth in global carbon sink dynamics. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (10), 4382–4387. https://doi.org/10.1073/pnas.1810512116

126. Walker, A.P., M.G. De Kauwe, A. Bastos, S. Belmecheri, K. Georgiou, R.F. Keeling, S.M. McMahon, B.E. Medlyn, D.J.P. Moore, R.J. Norby, S. Zaehle, K.J. Anderson-Teixeira, G. Battipaglia, R.J.W. Brienen, K.G. Cabugao, M. Cailleret, E. Campbell, J.G. Canadell, P. Ciais, M.E. Craig, D.S. Ellsworth, G.D. Farquhar, S. Fatichi, J.B. Fisher, D.C. Frank, H. Graven, L. Gu, V. Haverd, K. Heilman, M. Heimann, B.A. Hungate, C.M. Iversen, F. Joos, M. Jiang, T.F. Keenan, J. Knauer, C. Körner, V.O. Leshyk, S. Leuzinger, Y. Liu, N. MacBean, Y. Malhi, T.R. McVicar, J. Penuelas, J. Pongratz, A.S. Powell, T. Riutta, M.E.B. Sabot, J. Schleucher, S. Sitch, W.K. Smith, B. Sulman, B. Taylor, C. Terrer, M.S. Torn, K.K. Treseder, A.T. Trugman, S.E. Trumbore, P.J. van Mantgem, S.L. Voelker, M.E. Whelan, and P.A. Zuidema, 2021: Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric $CO_2$. *New Phytologist*, **229** (5), 2413–2445. https://doi.org/10.1111/nph.16866

127. Chen, Y., D.M. Romps, J.T. Seeley, S. Veraverbeke, W.J. Riley, Z.A. Mekonnen, and J.T. Randerson, 2021: Future increases in Arctic lightning and fire risk for permafrost carbon. *Nature Climate Change*, **11** (5), 404–410. https://doi.org/10.1038/s41558-021-01011-y

128. Bruhwiler, L., S. Basu, J.H. Butler, A. Chatterjee, E. Dlugokencky, M.A. Kenney, A. McComiskey, S.A. Montzka, and D. Stanitski, 2021: Observations of greenhouse gases as climate indicators. *Climatic Change*, **165** (1), 12. https://doi.org/10.1007/s10584-021-03001-7

129. Miner, K.R., M.R. Turetsky, E. Malina, A. Bartsch, J. Tamminen, A.D. McGuire, A. Fix, C. Sweeney, C.D. Elder, and C.E. Miller, 2022: Permafrost carbon emissions in a changing Arctic. *Nature Reviews Earth and Environment*, **3** (1), 55–67. https://doi.org/10.1038/s43017-021-00230-3

130. Busch, D.S. and P. McElhany, 2016: Estimates of the direct effect of seawater pH on the survival rate of species groups in the California Current ecosystem. *PLoS ONE*, **11** (8), e0160669. https://doi.org/10.1371/journal.pone.0160669

131. Heinze, C., S. Meyer, N. Goris, L. Anderson, R. Steinfeldt, N. Chang, C. Le Quéré, and D.C.E. Bakker, 2015: The ocean carbon sink—Impacts, vulnerabilities and challenges. *Earth System Dynamics*, **6** (1), 327–358. https://doi.org/10.5194/esd-6-327-2015

132. Jiang, L.-Q., B.R. Carter, R.A. Feely, S.K. Lauvset, and A. Olsen, 2019: Surface ocean pH and buffer capacity: Past, present and future. *Scientific Reports*, **9** (1), 18624. https://doi.org/10.1038/s41598-019-55039-4

133. Schlunegger, S., K.B. Rodgers, J.L. Sarmiento, T. Ilyina, J.P. Dunne, Y. Takano, J.R. Christian, M.C. Long, T.L. Frölicher, R. Slater, and F. Lehner, 2020: Time of emergence and large ensemble intercomparison for ocean biogeochemical trends. *Global Biogeochemical Cycles*, **34** (8), e2019GB006453. https://doi.org/10.1029/2019gb006453

134. Arora, V.K., A. Katavouta, R.G. Williams, C.D. Jones, V. Brovkin, P. Friedlingstein, J. Schwinger, L. Bopp, O. Boucher, P. Cadule, M.A. Chamberlain, J.R. Christian, C. Delire, R.A. Fisher, T. Hajima, T. Ilyina, E. Joetzjer, M. Kawamiya, C.D. Koven, J.P. Krasting, R.M. Law, D.M. Lawrence, A. Lenton, K. Lindsay, J. Pongratz, T. Raddatz, R. Séférian, K. Tachiiri, J.F. Tjiputra, A. Wiltshire, T. Wu, and T. Ziehn, 2020: Carbon–concentration and carbon–climate feedbacks in CMIP6 models and their comparison to CMIP5 models. *Biogeosciences*, **17** (16), 4173–4222. https://doi.org/10.5194/bg-17-4173-2020

135. Séférian, R., S. Berthet, A. Yool, J. Palmiéri, L. Bopp, A. Tagliabue, L. Kwiatkowski, O. Aumont, J. Christian, J. Dunne, M. Gehlen, T. Ilyina, J.G. John, H. Li, M.C. Long, J.Y. Luo, H. Nakano, A. Romanou, J. Schwinger, C. Stock, Y. Santana-Falcón, Y. Takano, J. Tjiputra, H. Tsujino, M. Watanabe, T. Wu, F. Wu, and A. Yamamoto, 2020: Tracking improvement in simulated marine biogeochemistry between CMIP5 and CMIP6. *Current Climate Change Reports*, **6** (3), 95–119. https://doi.org/10.1007/s40641-020-00160-0

136. Zhu, K., J. Zhang, S. Niu, C. Chu, and Y. Luo, 2018: Limits to growth of forest biomass carbon sink under climate change. *Nature Communications*, **9** (1), 2709. https://doi.org/10.1038/s41467-018-05132-5

137. Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Povak, and F.K. Lake, 2021: Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*, **31** (8), e02432. https://doi.org/10.1002/eap.2432

138. Talley, L., 2013: Closure of the global overturning circulation through the Indian, Pacific, and Southern Oceans: Schematics and transports. *Oceanography*, **26**, 80–97. https://doi.org/10.5670/oceanog.2013.07

139. Gruber, N., D. Clement, B.R. Carter, R.A. Feely, S. van Heuven, M. Hoppema, M. Ishii, R.M. Key, A. Kozyr, S.K. Lauvset, C. Lo Monaco, J.T. Mathis, A. Murata, A. Olsen, F.F. Perez, C.L. Sabine, T. Tanhua, and R. Wanninkhof, 2019: The oceanic sink for anthropogenic $CO_2$ from 1994 to 2007. *Science*, **363** (6432), 1193–1199. https://doi.org/10.1126/science.aau5153

140. Caesar, L., S. Rahmstorf, A. Robinson, G. Feulner, and V. Saba, 2018: Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, **556** (7700), 191–196. https://doi.org/10.1038/s41586-018-0006-5

141. Jackson, L.C. and R.A. Wood, 2020: Fingerprints for early detection of changes in the AMOC. *Journal of Climate*, **33** (16), 7027–7044. https://doi.org/10.1175/jcli-d-20-0034.1

142. IPCC, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964

143. Zanna, L., S. Khatiwala, J.M. Gregory, J. Ison, and P. Heimbach, 2019: Global reconstruction of historical ocean heat storage and transport. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (4), 1126–1131. https://doi.org/10.1073/pnas.1808838115

144. Hobday, A.J., L.V. Alexander, S.E. Perkins, D.A. Smale, S.C. Straub, E.C.J. Oliver, J.A. Benthuysen, M.T. Burrows, M.G. Donat, M. Feng, N.J. Holbrook, P.J. Moore, H.A. Scannell, A. Sen Gupta, and T. Wernberg, 2016: A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, **141**, 227–238. https://doi.org/10.1016/j.pocean.2015.12.014

145. Amaya, D.J., A.J. Miller, S.-P. Xie, and Y. Kosaka, 2020: Physical drivers of the summer 2019 North Pacific marine heatwave. *Nature Communications*, **11** (1), 1903. https://doi.org/10.1038/s41467-020-15820-w

146. Di Lorenzo, E. and N. Mantua, 2016: Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, **6**, 1042–1047. https://doi.org/10.1038/nclimate3082

147. Gentemann, C.L., M.R. Fewings, and M. García-Reyes, 2017: Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. *Geophysical Research Letters*, **44** (1), 312–319. https://doi.org/10.1002/2016gl071039

148. Markus, T., T. Neumann, A. Martino, W. Abdalati, K. Brunt, B. Csatho, S. Farrell, H. Fricker, A. Gardner, D. Harding, M. Jasinski, R. Kwok, L. Magruder, D. Lubin, S. Luthcke, J. Morison, R. Nelson, A. Neuenschwander, S. Palm, S. Popescu, C.K. Shum, B.E. Schutz, B. Smith, Y. Yang, and J. Zwally, 2017: The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2): Science requirements, concept, and implementation. *Remote Sensing of Environment*, **190**, 260–273. https://doi.org/10.1016/j.rse.2016.12.029

149. Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ch. 9. Ocean, cryosphere and sea level change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1211–1362. https://doi.org/10.1017/9781009157896.011

150. The Imbie Team, 2020: Mass balance of the Greenland ice sheet from 1992 to 2018. *Nature*, **579** (7798), 233–239. https://doi.org/10.1038/s41586-019-1855-2

151. DeConto, R.M. and D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise. *Nature*, **531** (7596), 591–597. https://doi.org/10.1038/nature17145

152. DeConto, R.M., D. Pollard, R.B. Alley, I. Velicogna, E. Gasson, N. Gomez, S. Sadai, A. Condron, D.M. Gilford, E.L. Ashe, R.E. Kopp, D. Li, and A. Dutton, 2021: The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature*, **593** (7857), 83–89. https://doi.org/10.1038/s41586-021-03427-0

153. Hoffman, M.J., X. Asay-Davis, S.F. Price, J. Fyke, and M. Perego, 2019: Effect of subshelf melt variability on sea level rise contribution from Thwaites Glacier, Antarctica. *Journal of Geophysical Research: Earth Surface*, **124** (12), e2019JF005155. https://doi.org/10.1029/2019jf005155

154. Joughin, I., B.E. Smith, and B. Medley, 2014: Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. *Science*, **344** (6185), 735–738. https://doi.org/10.1126/science.1249055

155. Morlighem, M., E. Rignot, T. Binder, D. Blankenship, R. Drews, G. Eagles, O. Eisen, F. Ferraccioli, R. Forsberg, P. Fretwell, V. Goel, J.S. Greenbaum, H. Gudmundsson, J. Guo, V. Helm, C. Hofstede, I. Howat, A. Humbert, W. Jokat, N.B. Karlsson, W.S. Lee, K. Matsuoka, R. Millan, J. Mouginot, J. Paden, F. Pattyn, J. Roberts, S. Rosier, A. Ruppel, H. Seroussi, E.C. Smith, D. Steinhage, B. Sun, M.R. van den Broeke, T.D. van Ommen, M. van Wessem, and D.A. Young, 2020: Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. *Nature Geoscience*, **13** (2), 132–137. https://doi.org/10.1038/s41561-019-0510-8

156. Robel, A.A., H. Seroussi, and G.H. Roe, 2019: Marine ice sheet instability amplifies and skews uncertainty in projections of future sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (30), 14887–14892. https://doi.org/10.1073/pnas.1904822116

157. Waibel, M.S., C.L. Hulbe, C.S. Jackson, and D.F. Martin, 2018: Rate of mass loss across the instability threshold for Thwaites Glacier determines rate of mass loss for entire basin. *Geophysical Research Letters*, **45** (2), 809–816. https://doi.org/10.1002/2017gl076470

158. Frederikse, T., F. Landerer, L. Caron, S. Adhikari, D. Parkes, V.W. Humphrey, S. Dangendorf, P. Hogarth, L. Zanna, L. Cheng, and Y.-H. Wu, 2020: The causes of sea-level rise since 1900. *Nature*, **584** (7821), 393–397. https://doi.org/10.1038/s41586-020-2591-3

159. Kemp, A.C., A.J. Wright, R.J. Edwards, R.L. Barnett, M.J. Brain, R.E. Kopp, N. Cahill, B.P. Horton, D.J. Charman, A.D. Hawkes, T.D. Hill, and O. van de Plassche, 2018: Relative sea-level change in Newfoundland, Canada during the past ¤3000 years. *Quaternary Science Reviews*, **201**, 89–110. https://doi.org/10.1016/j.quascirev.2018.10.012

160. Walker, J.S., R.E. Kopp, T.A. Shaw, N. Cahill, N.S. Khan, D.C. Barber, E.L. Ashe, M.J. Brain, J.L. Clear, D.R. Corbett, and B.P. Horton, 2021: Common Era sea-level budgets along the U.S. Atlantic coast. *Nature Communications*, **12** (1), 1841. https://doi.org/10.1038/s41467-021-22079-2

161. Dangendorf, S., C. Hay, F.M. Calafat, M. Marcos, C.G. Piecuch, K. Berk, and J. Jensen, 2019: Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change*, **9** (9), 705–710. https://doi.org/10.1038/s41558-019-0531-8

162. Nerem, R.S., B.D. Beckley, J.T. Fasullo, B.D. Hamlington, D. Masters, and G.T. Mitchum, 2018: Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (9), 2022–2025. https://doi.org/10.1073/pnas.1717312115

163. Hamlington, B.D., A.S. Gardner, E. Ivins, J.T.M. Lenaerts, J.T. Reager, D.S. Trossman, E.D. Zaron, S. Adhikari, A. Arendt, A. Aschwanden, B.D. Beckley, D.P.S. Bekaert, G. Blewitt, L. Caron, D.P. Chambers, H.A. Chandanpurkar, K. Christianson, B. Csatho, R.I. Cullather, R.M. DeConto, J.T. Fasullo, T. Frederikse, J.T. Freymueller, D.M. Gilford, M. Girotto, W.C. Hammond, R. Hock, N. Holschuh, R.E. Kopp, F. Landerer, E. Larour, D. Menemenlis, M. Merrifield, J.X. Mitrovica, R.S. Nerem, I.J. Nias, V. Nieves, S. Nowicki, K. Pangaluru, C.G. Piecuch, R.D. Ray, D.R. Rounce, N.-J. Schlegel, H. Seroussi, M. Shirzaei, W.V. Sweet, I. Velicogna, N. Vinogradova, T. Wahl, D.N. Wiese, and M.J. Willis, 2020: Understanding of contemporary regional sea-level change and the implications for the future. *Reviews of Geophysics*, **58** (3), e2019RG000672. https://doi.org/10.1029/2019rg000672

164. Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi, 2014: Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, **2** (8), 383–406. https://doi.org/10.1002/2014ef000239

165. Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas, 2017: Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 75 pp. https://repository.library.noaa.gov/view/noaa/18399

166. Gregory, J.M., S.M. Griffies, C.W. Hughes, J.A. Lowe, J.A. Church, I. Fukimori, N. Gomez, R.E. Kopp, F. Landerer, G.L. Cozannet, R.M. Ponte, D. Stammer, M.E. Tamisiea, and R.S.W. van de Wal, 2019: Concepts and terminology for sea level: Mean, variability and change, both local and global. *Surveys in Geophysics*, **40** (6), 1251–1289. https://doi.org/10.1007/s10712-019-09525-z

167. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

168. Thompson, P.R., M.J. Widlansky, B.D. Hamlington, M.A. Merrifield, J.J. Marra, G.T. Mitchum, and W. Sweet, 2021: Rapid increases and extreme months in projections of United States high-tide flooding. *Nature Climate Change*, **11** (7), 584–590. https://doi.org/10.1038/s41558-021-01077-8

169. Yin, J., S.M. Griffies, M. Winton, M. Zhao, and L. Zanna, 2020: Response of storm-related extreme sea level along the U.S. Atlantic coast to combined weather and climate forcing. *Journal of Climate*, **33** (9), 3745–3769. https://doi.org/10.1175/jcli-d-19-0551.1

170. Bintanja, R., E.C. van der Linden, and W. Hazeleger, 2012: Boundary layer stability and Arctic climate change: A feedback study using EC-Earth. *Climate Dynamics*, **39** (11), 2659–2673. https://doi.org/10.1007/s00382-011-1272-1

171. Walton, D.B., A. Hall, N. Berg, M. Schwartz, and F. Sun, 2017: Incorporating snow albedo feedback into downscaled temperature and snow cover projections for California's Sierra Nevada. *Journal of Climate*, **30** (4), 1417–1438. https://doi.org/10.1175/jcli-d-16-0168.1

172. Sun, F., A. Hall, M. Schwartz, D.B. Walton, and N. Berg, 2016: Twenty-first-century snowfall and snowpack changes over the Southern California mountains. *Journal of Climate*, **29** (1), 91–110. https://doi.org/10.1175/jcli-d-15-0199.1

173. Zhou, C., M.D. Zelinka, and S.A. Klein, 2016: Impact of decadal cloud variations on the Earth's energy budget. *Nature Geoscience*, **9** (12), 871–874. https://doi.org/10.1038/ngeo2828

174. Siler, N. and G. Roe, 2014: How will orographic precipitation respond to surface warming? An idealized thermodynamic perspective. *Geophysical Research Letters*, **41** (7), 2606–2613. https://doi.org/10.1002/2013gl059095

175. López-Moreno, J.I., S. Goyette, S.M. Vicente-Serrano, and M. Beniston, 2011: Effects of climate change on the intensity and frequency of heavy snowfall events in the Pyrenees. *Climatic Change*, **105** (3), 489–508. https://doi.org/10.1007/s10584-010-9889-3

176. Ohba, M. and H. Kawase, 2020: Rain-on-snow events in Japan as projected by a large ensemble of regional climate simulations. *Climate Dynamics*, **55** (9), 2785–2800. https://doi.org/10.1007/s00382-020-05419-8

177. Huang, X., D.L. Swain, and A.D. Hall, 2020: Future precipitation increase from very high resolution ensemble downscaling of extreme atmospheric river storms in California. *Science Advances*, **6** (29), 1323. https://doi.org/10.1126/sciadv.aba1323

178. Gula, J. and W.R. Peltier, 2012: Dynamical downscaling over the Great Lakes Basin of North America using the WRF regional climate model: The impact of the Great Lakes system on regional greenhouse warming. *Journal of Climate*, **25** (21), 7723–7742. https://doi.org/10.1175/jcli-d-11-00388.1

179. Liu, L., D. Shawki, A. Voulgarakis, M. Kasoar, B.H. Samset, G. Myhre, P.M. Forster, Ø. Hodnebrog, J. Sillmann, S.G. Aalbergsjø, O. Boucher, G. Faluvegi, T. Iversen, A. Kirkevåg, J.-F. Lamarque, D. Olivié, T. Richardson, D. Shindell, and T. Takemura, 2018: A PDRMIP multimodel study on the impacts of regional aerosol forcings on global and regional precipitation. *Journal of Climate*, **31** (11), 4429–4447. https://doi.org/10.1175/jcli-d-17-0439.1

180. Baldwin, J.W., J.B. Dessy, G.A. Vecchi, and M. Oppenheimer, 2019: Temporally compound heat wave events and global warming: An emerging hazard. *Earth's Future*, **7** (4), 411–427. https://doi.org/10.1029/2018ef000989

181. Sheridan, S.C. and C.C. Lee, 2018: Temporal trends in absolute and relative extreme temperature events across North America. *Journal of Geophysical Research: Atmospheres*, **123** (21), 11889–11898. https://doi.org/10.1029/2018jd029150

182. Cohen, J., L. Agel, M. Barlow, C.I. Garfinkel, and I. White, 2021: Linking Arctic variability and change with extreme winter weather in the United States. *Science*, **373** (6559), 1116–1121. https://doi.org/10.1126/science.abi9167

183. Barnes, E.A. and J.A. Screen, 2015: The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? *WIREs Climate Change*, **6** (3), 277–286. https://doi.org/10.1002/wcc.337

184. Blackport, R. and J.A. Screen, 2020: Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves. *Science Advances*, **6** (8), 2880. https://doi.org/10.1126/sciadv.aay2880

185. Chamberlain, C.J., B.I. Cook, I. Morales-Castilla, and E.M. Wolkovich, 2021: Climate change reshapes the drivers of false spring risk across European trees. *New Phytologist*, **229** (1), 323–334. https://doi.org/10.1111/nph.16851

186. Richardson, A.D., K. Hufkens, T. Milliman, D.M. Aubrecht, M.E. Furze, B. Seyednasrollah, M.B. Krassovski, J.M. Latimer, W.R. Nettles, R.R. Heiderman, J.M. Warren, and P.J. Hanson, 2018: Ecosystem warming extends vegetation activity but heightens vulnerability to cold temperatures. *Nature*, **560** (7718), 368–371. https://doi.org/10.1038/s41586-018-0399-1

187. Kirchmeier-Young, M.C. and X. Zhang, 2020: Human influence has intensified extreme precipitation in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (24), 13308–13313. https://doi.org/10.1073/pnas.1921628117

188. Kluver, D. and D. Leathers, 2015: Regionalization of snowfall frequency and trends over the contiguous United States. *International Journal of Climatology*, **35** (14), 4348–4358. https://doi.org/10.1002/joc.4292

189. Zarzycki, C.M., 2018: Projecting changes in societally impactful northeastern U.S. snowstorms. *Geophysical Research Letters*, **45** (21), 12067–12075. https://doi.org/10.1029/2018gl079820

190. Payne, A.E., M.-E. Demory, L.R. Leung, A.M. Ramos, C.A. Shields, J.J. Rutz, N. Siler, G. Villarini, A. Hall, and F.M. Ralph, 2020: Responses and impacts of atmospheric rivers to climate change. *Nature Reviews Earth & Environment*, **1** (3), 143–157. https://doi.org/10.1038/s43017-020-0030-5

191. Guzman, O. and H. Jiang, 2021: Global increase in tropical cyclone rain rate. *Nature Communications*, **12** (1), 5344. https://doi.org/10.1038/s41467-021-25685-2

192. Patricola, C.M. and M.F. Wehner, 2018: Anthropogenic influences on major tropical cyclone events. *Nature*, **563** (7731), 339–346. https://doi.org/10.1038/s41586-018-0673-2

193. Wilhite, D.A. and M.H. Glantz, 1985: Understanding: The drought phenomenon: The role of definitions. *Water International*, **10** (3), 111–120. https://doi.org/10.1080/02508068508686328

194. Cook, B.I., J.S. Mankin, and K.J. Anchukaitis, 2018: Climate change and drought: From past to future. *Current Climate Change Reports*, **4** (2), 164–179. https://doi.org/10.1007/s40641-018-0093-2

195. Swann, A.L.S., 2018: Plants and drought in a changing climate. *Current Climate Change Reports*, **4** (2), 192–201. https://doi.org/10.1007/s40641-018-0097-y

196. Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande, 2017: Ch. 8. Droughts, floods, and wildfires. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 231–256. https://doi.org/10.7930/j0cj8bnn

197. Fye, F.K., D.W. Stahle, and E.R. Cook, 2003: Paleoclimatic analogs to twentieth-century moisture regimes across the United States. *Bulletin of the American Meteorological Society*, **84** (7), 901–910. https://doi.org/10.1175/bams-84-7-901

198. Cook, B.I., E.R. Cook, J.E. Smerdon, R. Seager, A.P. Williams, S. Coats, D.W. Stahle, and J.V. Díaz, 2016: North American megadroughts in the Common Era: Reconstructions and simulations. *Wiley Interdisciplinary Reviews: Climate Change*, **7** (3), 411–432. https://doi.org/10.1002/wcc.394

199. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. https://doi.org/10.1038/s41558-022-01290-z

200. Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, J.T. Abatzoglou, K. Bolles, S.H. Baek, A.M. Badger, and B. Livneh, 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368** (6488), 314–318. https://doi.org/10.1126/science.aaz9600

201. Douville, H., K. Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T.Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina, 2021: Ch. 8. Water cycle changes. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1055–1210. https://doi.org/10.1017/9781009157896.010

202. Marvel, K., B.I. Cook, C. Bonfils, J.E. Smerdon, A.P. Williams, and H. Liu, 2021: Projected changes to hydroclimate seasonality in the continental United States. *Earth's Future*, **9** (9), e2021EF002019. https://doi.org/10.1029/2021ef002019

203. Stevenson, S., S. Coats, D. Touma, J. Cole, F. Lehner, J. Fasullo, and B. Otto-Bliesner, 2022: Twenty-first century hydroclimate: A continually changing baseline, with more frequent extremes. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (12), e2108124119. https://doi.org/10.1073/pnas.2108124119

204. Su, L., Q. Cao, M. Xiao, D.M. Mocko, M. Barlage, D. Li, C.D. Peters-Lidard, and D.P. Lettenmaier, 2021: Drought variability over the conterminous United States for the past century. *Journal of Hydrometeorology*, **22** (5), 1153–1168. https://doi.org/10.1175/jhm-d-20-0158.1

205. Hoell, A., M. Hoerling, X.-W. Quan, and R. Robinson, 2023: Recent high Missouri River Basin runoff was unlikely due to climate change. *Journal of Applied Meteorology and Climatology*, **62** (6), 657–675. https://doi.org/10.1175/jamc-d-22-0158.1

206. Cook, B.I., T.R. Ault, and J.E. Smerdon, 2015: Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances*, **1** (1), e1400082. https://doi.org/10.1126/sciadv.1400082

207. Cook, B.I., J.S. Mankin, K. Marvel, A.P. Williams, J.E. Smerdon, and K.J. Anchukaitis, 2020: Twenty-first century drought projections in the CMIP6 forcing scenarios. *Earth's Future*, **8** (6), e2019EF001461. https://doi.org/10.1029/2019ef001461

208. Cook, B.I., J.S. Mankin, A.P. Williams, K.D. Marvel, J.E. Smerdon, and H. Liu, 2021: Uncertainties, limits, and benefits of climate change mitigation for soil moisture drought in southwestern North America. *Earth's Future*, **9** (9), e2021EF002014. https://doi.org/10.1029/2021ef002014

209. Berg, N. and A. Hall, 2017: Anthropogenic warming impacts on California snowpack during drought. *Geophysical Research Letters*, **44** (5), 2511–2518. https://doi.org/10.1002/2016gl072104

210. Griffin, D. and K.J. Anchukaitis, 2014: How unusual is the 2012–2014 California drought? *Geophysical Research Letters*, **41** (24), 9017–9023. https://doi.org/10.1002/2014gl062433

211. Williams, A.P., R. Seager, J.T. Abatzoglou, B.I. Cook, J.E. Smerdon, and E.R. Cook, 2015: Contribution of anthropogenic warming to California drought during 2012–2014. *Geophysical Research Letters*, **42** (16), 6819–6828. https://doi.org/10.1002/2015gl064924

212. Marlier, M.E., M. Xiao, R. Engel, B. Livneh, J.T. Abatzoglou, and D.P. Lettenmaier, 2017: The 2015 drought in Washington State: A harbinger of things to come? *Environmental Research Letters*, **12** (11), 114008. https://doi.org/10.1088/1748-9326/aa8fde

213. Mote, P.W., D.E. Rupp, S. Li, D.J. Sharp, F. Otto, P.F. Uhe, M. Xiao, D.P. Lettenmaier, H. Cullen, and M.R. Allen, 2016: Perspectives on the causes of exceptionally low 2015 snowpack in the western United States. *Geophysical Research Letters*, **43**, 10980–10988. https://doi.org/10.1002/2016gl069965

214. Xiao, M., B. Udall, and D.P. Lettenmaier, 2018: On the causes of declining Colorado River streamflows. *Water Resources Research*, **54** (9), 6739–6756. https://doi.org/10.1029/2018wr023153

215. Mankin, J.S., R. Seager, J.E. Smerdon, B.I. Cook, and A.P. Williams, 2019: Mid-latitude freshwater availability reduced by projected vegetation responses to climate change. *Nature Geoscience*, **12** (12), 983–988. https://doi.org/10.1038/s41561-019-0480-x

216. Abatzoglou, J.T., C.S. Juang, A.P. Williams, C.A. Kolden, and A.L. Westerling, 2021: Increasing synchronous fire danger in forests of the western United States. *Geophysical Research Letters*, **48** (2), e2020GL091377. https://doi.org/10.1029/2020gl091377

217. Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (42), 11770–11775. https://doi.org/10.1073/pnas.1607171113

218. Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara, 2021: The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2011048118. https://doi.org/10.1073/pnas.2011048118

219. Williams, A.P., J.T. Abatzoglou, A. Gershunov, J. Guzman-Morales, D.A. Bishop, J.K. Balch, and D.P. Lettenmaier, 2019: Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future*, **7** (8), 892–910. https://doi.org/10.1029/2019ef001210

220. Abatzoglou, J.T., D.S. Battisti, A.P. Williams, W.D. Hansen, B.J. Harvey, and C.A. Kolden, 2021: Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth & Environment*, **2** (1), 227. https://doi.org/10.1038/s43247-021-00299-0

221. Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A.D. Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, 2021: Ch. 11. Weather and climate extreme events in a changing climate. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1513–1766. https://doi.org/10.1017/9781009157896.013

222. Zhang, W., M. Luo, S. Gao, W. Chen, V. Hari, and A. Khouakhi, 2021: Compound hydrometeorological extremes: Drivers, mechanisms and methods. *Frontiers in Earth Science*, **9**, 673495. https://doi.org/10.3389/feart.2021.673495

223. Zscheischler, J., O. Martius, S. Westra, E. Bevacqua, C. Raymond, R.M. Horton, B. van den Hurk, A. AghaKouchak, A. Jézéquel, M.D. Mahecha, D. Maraun, A.M. Ramos, N.N. Ridder, W. Thiery, and E. Vignotto, 2020: A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, **1** (7), 333–347. https://doi.org/10.1038/s43017-020-0060-z

224. Boers, N., B. Goswami, A. Rheinwalt, B. Bookhagen, B. Hoskins, and J. Kurths, 2019: Complex networks reveal global pattern of extreme-rainfall teleconnections. *Nature*, **566** (7744), 373–377. https://doi.org/10.1038/s41586-018-0872-x

225. Cooley, D., E. Thibaud, F. Castillo, and M.F. Wehner, 2019: A nonparametric method for producing isolines of bivariate exceedance probabilities. *Extremes*, **22** (3), 373–390. https://doi.org/10.1007/s10687-019-00348-0

226. Donges, J.F., C.F. Schleussner, J.F. Siegmund, and R.V. Donner, 2016: Event coincidence analysis for quantifying statistical interrelationships between event time series. *The European Physical Journal Special Topics*, **225** (3), 471–487. https://doi.org/10.1140/epjst/e2015-50233-y

227. Sadegh, M., E. Ragno, and A. AghaKouchak, 2017: Multivariate Copula Analysis Toolbox (MvCAT): Describing dependence and underlying uncertainty using a Bayesian framework. *Water Resources Research*, **53** (6), 5166–5183. https://doi.org/10.1002/2016wr020242

228. Bevacqua, E., C. De Michele, C. Manning, A. Couasnon, A.F.S. Ribeiro, A.M. Ramos, E. Vignotto, A. Bastos, S. Blesić, F. Durante, J. Hillier, S.C. Oliveira, J.G. Pinto, E. Ragno, P. Rivoire, K. Saunders, K. van der Wiel, W. Wu, T. Zhang, and J. Zscheischler, 2021: Guidelines for studying diverse types of compound weather and climate events. *Earth's Future*, **9** (11), e2021EF002340. https://doi.org/10.1029/2021ef002340

229. Raymond, C., R.M. Horton, J. Zscheischler, O. Martius, A. AghaKouchak, J. Balch, S.G. Bowen, S.J. Camargo, J. Hess, K. Kornhuber, M. Oppenheimer, A.C. Ruane, T. Wahl, and K. White, 2020: Understanding and managing connected extreme events. *Nature Climate Change*, **10** (7), 611–621. https://doi.org/10.1038/s41558-020-0790-4

230. AghaKouchak, A., F. Chiang, L.S. Huning, C.A. Love, I. Mallakpour, O. Mazdiyasni, H. Moftakhari, S.M. Papalexiou, E. Ragno, and M. Sadegh, 2020: Climate extremes and compound hazards in a warming world. *Annual Review of Earth and Planetary Sciences*, **48** (1), 519–548. https://doi.org/10.1146/annurev-earth-071719-055228

231. Arrhenius, S., 1896: On the influence of carbonic acid in the air upon the temperature of the ground. *Philosophical Magazine and Journal of Science*, **41**, 237–276. https://www.rsc.org/images/arrhenius1896_tcm18-173546.pdf

232. Foote, E., 1856: Circumstances affecting the heat of the sun's rays. *The American Journal of Science and Arts*, **22** (66), 383–384. https://www.davidmorrow.net/eunice-foote

233. Tyndall, J., 1861: The Bakerian Lecture: On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absoprtion, and conduction. *Philosophical Transactions of the Royal Society of London*, **151**, 1–36. https://doi.org/10.1098/rstl.1861.0001

234. Ramaswamy, V., W. Collins, J. Haywood, J. Lean, N. Mahowald, G. Myhre, V. Naik, K.P. Shine, B. Soden, G. Stenchikov, and T. Storelvmo, 2019: Radiative forcing of climate: The historical evolution of the radiative forcing concept, the forcing agents and their quantification, and applications. *Meteorological Monographs*, **59** (1). https://doi.org/10.1175/amsmonographs-d-19-0001.1

235. Eyring, V., N.P. Gillett, K.M.A. Rao, R. Barimalala, M.B. Parrillo, N. Bellouin, C. Cassou, P.J. Durack, Y. Kosaka, S. McGregor, S. Min, O. Morgenstern, and Y. Sun, 2021: Ch. 3. Human influence on the climate system. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 423–552. https://doi.org/10.1017/9781009157896.005

236. Saunois, M., A.R. Stavert, B. Poulter, P. Bousquet, J.G. Canadell, R.B. Jackson, P.A. Raymond, E.J. Dlugokencky, S. Houweling, P.K. Patra, P. Ciais, V.K. Arora, D. Bastviken, P. Bergamaschi, D.R. Blake, G. Brailsford, L. Bruhwiler, K.M. Carlson, M. Carrol, S. Castaldi, N. Chandra, C. Crevoisier, P.M. Crill, K. Covey, C.L. Curry, G. Etiope, C. Frankenberg, N. Gedney, M.I. Hegglin, L. Höglund-Isaksson, G. Hugelius, M. Ishizawa, A. Ito, G. Janssens-Maenhout, K.M. Jensen, F. Joos, T. Kleinen, P.B. Krummel, R.L. Langenfelds, G.G. Laruelle, L. Liu, T. Machida, S. Maksyutov, K.C. McDonald, J. McNorton, P.A. Miller, J.R. Melton, I. Morino, J. Müller, F. Murguia-Flores, V. Naik, Y. Niwa, S. Noce, S. O'Doherty, R.J. Parker, C. Peng, S. Peng, G.P. Peters, C. Prigent, R. Prinn, M. Ramonet, P. Regnier, W.J. Riley, J.A. Rosentreter, A. Segers, I.J. Simpson, H. Shi, S.J. Smith, L.P. Steele, B.F. Thornton, H. Tian, Y. Tohjima, F.N. Tubiello, A. Tsuruta, N. Viovy, A. Voulgarakis, T.S. Weber, M. van Weele, G.R. van der Werf, R.F. Weiss, D. Worthy, D. Wunch, Y. Yin, Y. Yoshida, W. Zhang, Z. Zhang, Y. Zhao, B. Zheng, Q. Zhu, Q. Zhu, and Q. Zhuang, 2020: The global methane budget 2000–2017. *Earth System Science Data*, **12** (3), 1561–1623. https://doi.org/10.5194/essd-12-1561-2020

237. Tans, P., 2009: An accounting of the observed increase in oceanic and atmospheric $CO_2$ and an outlook for the future. *Oceanography*, **22** (4), 26–35. https://doi.org/10.5670/oceanog.2009.94

238. Basu, S., X. Lan, E. Dlugokencky, S. Michel, S. Schwietzke, J.B. Miller, L. Bruhwiler, Y. Oh, P.P. Tans, F. Apadula, L.V. Gatti, A. Jordan, J. Necki, M. Sasakawa, S. Morimoto, T. Di Iorio, H. Lee, J. Arduini, and G. Manca, 2022: Estimating emissions of methane consistent with atmospheric measurements of methane and $\delta^{13}C$ of methane. *Atmospheric Chemistry and Physics*, **22** (23), 15351–15377. https://doi.org/10.5194/acp-22-15351-2022

239. Schwietzke, S., O.A. Sherwood, L.M.P. Bruhwiler, J.B. Miller, G. Etiope, E.J. Dlugokencky, S.E. Michel, V.A. Arling, B.H. Vaughn, J.W.C. White, and P.P. Tans, 2016: Upward revision of global fossil fuel methane emissions based on isotope database. *Nature*, **538** (7623), 88–91. https://doi.org/10.1038/nature19797

240. Ceppi, P. and P. Nowack, 2021: Observational evidence that cloud feedback amplifies global warming. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (30), e2026290118. https://doi.org/10.1073/pnas.2026290118

241. Dessler, A.E., 2013: Observations of climate feedbacks over 2000–10 and comparisons to climate models. *Journal of Climate*, **26** (1), 333–342. https://doi.org/10.1175/jcli-d-11-00640.1

242. Klein, S.A., A. Hall, J.R. Norris, and R. Pincus, 2017: Low-cloud feedbacks from cloud-controlling factors: A review. *Surveys in Geophysics*, **38** (6), 1307–1329. https://doi.org/10.1007/s10712-017-9433-3

243. McCoy, D.T., P. Field, A. Bodas-Salcedo, G.S. Elsaesser, and M.D. Zelinka, 2020: A regime-oriented approach to observationally constraining extratropical shortwave cloud feedbacks. *Journal of Climate*, **33** (23), 9967–9983. https://doi.org/10.1175/jcli-d-19-0987.1

244. Vaillant de Guélis, T., H. Chepfer, R. Guzman, M. Bonazzola, D.M. Winker, and V. Noel, 2018: Space lidar observations constrain longwave cloud feedback. *Scientific Reports*, **8** (1), 16570. https://doi.org/10.1038/s41598-018-34943-1

245. Williams, I.N. and R.T. Pierrehumbert, 2017: Observational evidence against strongly stabilizing tropical cloud feedbacks. *Geophysical Research Letters*, **44** (3), 1503–1510. https://doi.org/10.1002/2016gl072202

246. Klein, S.A. and A. Hall, 2015: Emergent constraints for cloud feedbacks. *Current Climate Change Reports*, **1** (4), 276–287. https://doi.org/10.1007/s40641-015-0027-1

247. Thackeray, C.W., A. Hall, M.D. Zelinka, and C.G. Fletcher, 2021: Assessing prior emergent constraints on surface albedo feedback in CMIP6. *Journal of Climate*, **34** (10), 3889–3905. https://doi.org/10.1175/jcli-d-20-0703.1

248. Lenssen, N.J.L., G.A. Schmidt, J.E. Hansen, M.J. Menne, A. Persin, R. Ruedy, and D. Zyss, 2019: Improvements in the GISTEMP uncertainty model. *Journal of Geophysical Research: Atmospheres*, **124** (12), 6307–6326. https://doi.org/10.1029/2018jd029522

249. Morice, C.P., J.J. Kennedy, N.A. Rayner, J.P. Winn, E. Hogan, R.E. Killick, R.J.H. Dunn, T.J. Osborn, P.D. Jones, and I.R. Simpson, 2021: An updated assessment of near-surface temperature change from 1850: The HadCRUT5 data set. *Journal of Geophysical Research: Atmospheres*, **126** (3), e2019JD032361. https://doi.org/10.1029/2019jd032361

250. Andrews, T., J.M. Gregory, and M.J. Webb, 2015: The dependence of radiative forcing and feedback on evolving patterns of surface temperature change in climate models. *Journal of Climate*, **28** (4), 1630–1648. https://doi.org/10.1175/jcli-d-14-00545.1

251. Kageyama, M., S. Albani, P. Braconnot, S.P. Harrison, P.O. Hopcroft, R.F. Ivanovic, F. Lambert, O. Marti, W.R. Peltier, J.Y. Peterschmitt, D.M. Roche, L. Tarasov, X. Zhang, E.C. Brady, A.M. Haywood, A.N. LeGrande, D.J. Lunt, N.M. Mahowald, U. Mikolajewicz, K.H. Nisancioglu, B.L. Otto-Bliesner, H. Renssen, R.A. Tomas, Q. Zhang, A. Abe-Ouchi, P.J. Bartlein, J. Cao, Q. Li, G. Lohmann, R. Ohgaito, X. Shi, E. Volodin, K. Yoshida, X. Zhang, and W. Zheng, 2017: The PMIP4 contribution to CMIP6—Part 4: Scientific objectives and experimental design of the PMIP4-CMIP6 Last Glacial Maximum experiments and PMIP4 sensitivity experiments. *Geoscientific Model Development*, **10** (11), 4035–4055. https://doi.org/10.5194/gmd-10-4035-2017

252. Haywood, A.M., H.J. Dowsett, and A.M. Dolan, 2016: Integrating geological archives and climate models for the mid-Pliocene warm period. *Nature Communications*, **7** (1), 10646. https://doi.org/10.1038/ncomms10646

253. Lunt, D.J., M. Huber, E. Anagnostou, M.L.J. Baatsen, R. Caballero, R. DeConto, H.A. Dijkstra, Y. Donnadieu, D. Evans, R. Feng, G.L. Foster, E. Gasson, A.S. von der Heydt, C.J. Hollis, G.N. Inglis, S.M. Jones, J. Kiehl, S. Kirtland Turner, R.L. Korty, R. Kozdon, S. Krishnan, J.B. Ladant, P. Langebroek, C.H. Lear, A.N. LeGrande, K. Littler, P. Markwick, B. Otto-Bliesner, P. Pearson, C.J. Poulsen, U. Salzmann, C. Shields, K. Snell, M. Stärz, J. Super, C. Tabor, J.E. Tierney, G.J.L. Tourte, A. Tripati, G.R. Upchurch, B.S. Wade, S.L. Wing, A.M.E. Winguth, N.M. Wright, J.C. Zachos, and R.E. Zeebe, 2017: The DeepMIP contribution to PMIP4: Experimental design for model simulations of the EECO, PETM, and pre-PETM (version 1.0). *Geoscientific Model Development*, **10** (2), 889–901. https://doi.org/10.5194/gmd-10-889-2017

254. Köhler, P., R. Bintanja, H. Fischer, F. Joos, R. Knutti, G. Lohmann, and V. Masson-Delmotte, 2010: What caused Earth's temperature variations during the last 800,000 years? Data-based evidence on radiative forcing and constraints on climate sensitivity. *Quaternary Science Reviews*, **29** (1), 129–145. https://doi.org/10.1016/j.quascirev.2009.09.026

255. von der Heydt, A.S. and P. Ashwin, 2017: State dependence of climate sensitivity: Attractor constraints and palaeoclimate regimes. *Dynamics and Statistics of the Climate System*, **1** (1). https://doi.org/10.1093/climsys/dzx001

256. Sherwood, S.C., S. Bony, O. Boucher, C. Bretherton, P.M. Forster, J.M. Gregory, and B. Stevens, 2015: Adjustments in the forcing-feedback framework for understanding climate change. *Bulletin of the American Meteorological Society*, **96** (2), 217–228. https://doi.org/10.1175/bams-d-13-00167.1

257. Harris, D.C., 2010: Charles David Keeling and the story of atmospheric $CO_2$ measurements. *Analytical Chemistry*, **82** (19), 7865–7870. https://doi.org/10.1021/ac1001492

258. Kansakar, P. and F. Hossain, 2016: A review of applications of satellite earth observation data for global societal benefit and stewardship of planet earth. *Space Policy*, **36**, 46–54. https://doi.org/10.1016/j.spacepol.2016.05.005

259. Novick, K.A., J.A. Biederman, A.R. Desai, M.E. Litvak, D.J.P. Moore, R.L. Scott, and M.S. Torn, 2018: The AmeriFlux network: A coalition of the willing. *Agricultural and Forest Meteorology*, **249**, 444–456. https://doi.org/10.1016/j.agrformet.2017.10.009

260. Chabbi, A. and H.W. Loescher, Eds., 2016: *Terrestrial Ecosystem Research Infrastructures: Challenges and Opportunities*. 1st ed., CRC Press, 558 pp. https://doi.org/10.1201/9781315368252

261. USGS, 2019: Surface Runoff and the Water Cycle. U.S. Geological Survey. https://www.usgs.gov/special-topics/water-science-school/science/surface-runoff-and-water-cycle#overview

262. Wild, M., 2017: Towards global estimates of the surface energy budget. *Current Climate Change Reports*, **3** (1), 87–97. https://doi.org/10.1007/s40641-017-0058-x

263. Montzka, S.A., 2022: NOAA's Annual Greenhouse Gas Index. National Oceanic and Atmospheric Administration, Global Monitoring Laboratory, accessed June 10, 2022. https://gml.noaa.gov/aggi/

264. Lumpkin, R., T. Özgökmen, and L. Centurioni, 2017: Advances in the application of surface drifters. *Annual Review of Marine Science*, **9** (1), 59–81. https://doi.org/10.1146/annurev-marine-010816-060641

265. Williams, N.L., L.W. Juranek, R.A. Feely, K.S. Johnson, J.L. Sarmiento, L.D. Talley, A.G. Dickson, A.R. Gray, R. Wanninkhof, J.L. Russell, S.C. Riser, and Y. Takeshita, 2017: Calculating surface ocean $pCO_2$ from biogeochemical Argo floats equipped with pH: An uncertainty analysis. *Global Biogeochemical Cycles*, **31** (3), 591–604. https://doi.org/10.1002/2016gb005541

266. Loeb, N.G., G.C. Johnson, T.J. Thorsen, J.M. Lyman, F.G. Rose, and S. Kato, 2021: Satellite and ocean data reveal marked increase in Earth's heating rate. *Geophysical Research Letters*, **48** (13), e2021GL093047. https://doi.org/10.1029/2021gl093047

267. Susskind, J., G.A. Schmidt, J.N. Lee, and L. Iredell, 2019: Recent global warming as confirmed by AIRS. *Environmental Research Letters*, **14** (4), 044030. https://doi.org/10.1088/1748-9326/aafd4e

268. Li, Z., J. Guo, B. Ji, X. Wan, and S. Zhang, 2022: A review of marine gravity field recovery from satellite altimetry. *Remote Sensing*, **14** (19). https://doi.org/10.3390/rs14194790

269. Fisher, J.B., B. Lee, A.J. Purdy, G.H. Halverson, M.B. Dohlen, K. Cawse-Nicholson, A. Wang, R.G. Anderson, B. Aragon, M.A. Arain, D.D. Baldocchi, J.M. Baker, H. Barral, C.J. Bernacchi, C. Bernhofer, S.C. Biraud, G. Bohrer, N. Brunsell, B. Cappelaere, S. Castro-Contreras, J. Chun, B.J. Conrad, E. Cremonese, J. Demarty, A.R. Desai, A. De Ligne, L. Foltýnová, M.L. Goulden, T.J. Griffis, T. Grünwald, M.S. Johnson, M. Kang, D. Kelbe, N. Kowalska, J.-H. Lim, I. Maïnassara, M.F. McCabe, J.E.C. Missik, B.P. Mohanty, C.E. Moore, L. Morillas, R. Morrison, J.W. Munger, G. Posse, A.D. Richardson, E.S. Russell, Y. Ryu, A. Sanchez-Azofeifa, M. Schmidt, E. Schwartz, I. Sharp, L. Šigut, Y. Tang, G. Hulley, M. Anderson, C. Hain, A. French, E. Wood, and S. Hook, 2020: ECOSTRESS: NASA's next generation mission to measure evapotranspiration from the International Space Station. *Water Resources Research*, **56** (4), e2019WR026058. https://doi.org/10.1029/2019wr026058

270. Dubayah, R., J.B. Blair, S. Goetz, L. Fatoyinbo, M. Hansen, S. Healey, M. Hofton, G. Hurtt, J. Kellner, S. Luthcke, J. Armston, H. Tang, L. Duncanson, S. Hancock, P. Jantz, S. Marselis, P.L. Patterson, W. Qi, and C. Silva, 2020: The Global Ecosystem Dynamics Investigation: High-resolution laser ranging of the Earth's forests and topography. *Science of Remote Sensing*, **1**, 100002. https://doi.org/10.1016/j.srs.2020.100002

271. Green, R.O., N. Mahowald, C. Ung, D.R. Thompson, L. Bator, M. Bennet, M. Bernas, N. Blackway, C. Bradley, J. Cha, P. Clark, R. Clark, D. Cloud, E. Diaz, E.B. Dor, R. Duren, M. Eastwood, B.L. Ehlmann, L. Fuentes, P. Ginoux, J. Gross, Y. He, O. Kalashnikova, W. Kert, D. Keymeulen, M. Klimesh, D. Ku, H. Kwong-Fu, E. Liggett, L. Li, S. Lundeen, M.D. Makowski, A. Mazer, R. Miller, P. Mouroulis, B. Oaida, G.S. Okin, A. Ortega, A. Oyake, H. Nguyen, T. Pace, T.H. Painter, J. Pempejian, C.P. Garcia-Pando, T. Pham, B. Phillips, R. Pollock, R. Purcell, V. Realmuto, J. Schoolcraft, A. Sen, S. Shin, L. Shaw, M. Soriano, G. Swayze, E. Thingvold, A. Vaid, and J. Zan, 2020: The Earth surface mineral dust source investigation: An earth science imaging spectroscopy mission. In: *2020 IEEE Aerospace Conference*. 7–14 March 2020, 1–15. https://doi.org/10.1109/aero47225.2020.9172731

272. Zavodsky, B., J. Dunion, W. Blackwell, S. Braun, C. Velden, M. Brennan, and R. Adler, 2017: First Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats (TROPICS) mission applications workshop summary report. 8–10 May 2017. National Aeronautics and Space Administration, Earth Science Division Applied Science Program. https://ntrs.nasa.gov/api/citations/20170010652/downloads/20170010652.pdf

273. Goldberg, M. and L. Zhou, 2017: The joint polar satellite system—Overview, instruments, proving ground and risk reduction activities. In: *2017 IEEE International Geoscience and Remote Sensing Symposium* (IGARSS). 23–28 July 2017, 2776–2778. https://doi.org/10.1109/igarss.2017.8127573

274. Morrow, R., L.-L. Fu, F. Ardhuin, M. Benkiran, B. Chapron, E. Cosme, F. d'Ovidio, J.T. Farrar, S.T. Gille, G. Lapeyre, P.-Y. Le Traon, A. Pascual, A. Ponte, B. Qiu, N. Rascle, C. Ubelmann, J. Wang, and E.D. Zaron, 2019: Global observations of fine-scale ocean surface topography with the Surface Water and Ocean Topography (SWOT) mission. *Frontiers in Marine Science*, **6**, 232. https://doi.org/10.3389/fmars.2019.00232

275. Painter, T.H., D.F. Berisford, J.W. Boardman, K.J. Bormann, J.S. Deems, F. Gehrke, A. Hedrick, M. Joyce, R. Laidlaw, D. Marks, C. Mattmann, B. McGurk, P. Ramirez, M. Richardson, S.M. Skiles, F.C. Seidel, and A. Winstral, 2016: The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo. *Remote Sensing of Environment*, **184**, 139–152. https://doi.org/10.1016/j.rse.2016.06.018

276. Eberts, S.M., C.R. Wagner, and M.D. Woodside, 2019: Water priorities for the Nation—The U.S. Geological Survey Next Generation Water Observing System. USGS Fact Sheet 2019–3046. U.S. Geological Survey, 2 pp. https://doi.org/10.3133/fs20193046

277. Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756. https://doi.org/10.1038/nature08823

278. IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1535 pp. https://www.ipcc.ch/report/ar5/wg1/

279. Ebi, K.L., S. Hallegatte, T. Kram, N.W. Arnell, T.R. Carter, J. Edmonds, E. Kriegler, R. Mathur, B.C. O'Neill, K. Riahi, H. Winkler, D.P. Van Vuuren, and T. Zwickel, 2014: A new scenario framework for climate change research: Background, process, and future directions. *Climatic Change*, **122** (3), 363–372. https://doi.org/10.1007/s10584-013-0912-3

280. Tebaldi, C., K. Debeire, V. Eyring, E. Fischer, J. Fyfe, P. Friedlingstein, R. Knutti, J. Lowe, B. O'Neill, B. Sanderson, D. van Vuuren, K. Riahi, M. Meinshausen, Z. Nicholls, K.B. Tokarska, G. Hurtt, E. Kriegler, J.F. Lamarque, G. Meehl, R. Moss, S.E. Bauer, O. Boucher, V. Brovkin, Y.H. Byun, M. Dix, S. Gualdi, H. Guo, J.G. John, S. Kharin, Y. Kim, T. Koshiro, L. Ma, D. Olivié, S. Panickal, F. Qiao, X. Rong, N. Rosenbloom, M. Schupfner, R. Séférian, A. Sellar, T. Semmler, X. Shi, Z. Song, C. Steger, R. Stouffer, N. Swart, K. Tachiiri, Q. Tang, H. Tatebe, A. Voldoire, E. Volodin, K. Wyser, X. Xin, S. Yang, Y. Yu, and T. Ziehn, 2021: Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth System Dynamics*, **12** (1), 253–293. https://doi.org/10.5194/esd-12-253-2021

281. Deser, C., R. Knutti, S. Solomon, and A.S. Phillips, 2012: Communication of the role of natural variability in future North American climate. *Nature Climate Change*, **2** (11), 775–779. https://doi.org/10.1038/nclimate1562

282. Deser, C., A. Phillips, V. Bourdette, and H. Teng, 2012: Uncertainty in climate change projections: The role of internal variability. *Climate Dynamics*, **38** (3–4), 527–546. https://doi.org/10.1007/s00382-010-0977-x

283. Rodgers, K.B., J. Lin, and T.L. Frölicher, 2015: Emergence of multiple ocean ecosystem drivers in a large ensemble suite with an Earth system model. *Biogeosciences*, **12** (11), 3301–3320. https://doi.org/10.5194/bg-12-3301-2015

284. Maher, N., S. Milinski, L. Suarez-Gutierrez, M. Botzet, M. Dobrynin, L. Kornblueh, J. Kröger, Y. Takano, R. Ghosh, C. Hedemann, C. Li, H. Li, E. Manzini, D. Notz, D. Putrasahan, L. Boysen, M. Claussen, T. Ilyina, D. Olonscheck, T. Raddatz, B. Stevens, and J. Marotzke, 2019: The Max Planck Institute Grand ensemble: Enabling the exploration of climate system variability. *Journal of Advances in Modeling Earth Systems*, **11** (7), 2050–2069. https://doi.org/10.1029/2019ms001639

285. Pendergrass, A.G., D.B. Coleman, C. Deser, F. Lehner, N. Rosenbloom, and I.R. Simpson, 2019: Nonlinear response of extreme precipitation to warming in CESM1. *Geophysical Research Letters*, **46** (17-18), 10551–10560. https://doi.org/10.1029/2019gl084826

286. Cai, W., A. Santoso, M. Collins, B. Dewitte, C. Karamperidou, J.-S. Kug, M. Lengaigne, M.J. McPhaden, M.F. Stuecker, A.S. Taschetto, A. Timmermann, L. Wu, S.-W. Yeh, G. Wang, B. Ng, F. Jia, Y. Yang, J. Ying, X.-T. Zheng, T. Bayr, J.R. Brown, A. Capotondi, K.M. Cobb, B. Gan, T. Geng, Y.-G. Ham, F.-F. Jin, H.-S. Jo, X. Li, X. Lin, S. McGregor, J.-H. Park, K. Stein, K. Yang, L. Zhang, and W. Zhong, 2021: Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment*, **2** (9), 628–644. https://doi.org/10.1038/s43017-021-00199-z

287. Haszpra, T., M. Herein, and T. Bódai, 2020: Investigating ENSO and its teleconnections under climate change in an ensemble view–A new perspective. *Earth System Dynamics*, **11** (1), 267–280. https://doi.org/10.5194/esd-11-267-2020

288. Maher, N., D. Matei, S. Milinski, and J. Marotzke, 2018: ENSO change in climate projections: Forced response or internal variability? *Geophysical Research Letters*, **45** (20), 11390–11398. https://doi.org/10.1029/2018gl079764

289. O'Brien, J.P. and C. Deser, 2022: Quantifying and understanding forced changes to unforced modes of atmospheric circulation variability over the North Pacific in a coupled model large ensemble. *Journal of Climate*, **36** (1), 19–37. https://doi.org/10.1175/jcli-d-22-0101.1

290. Milinski, S., N. Maher, and D. Olonscheck, 2020: How large does a large ensemble need to be? *Earth System Dynamics*, **11** (4), 885–901. https://doi.org/10.5194/esd-11-885-2020

291. Mankin, J.S., F. Lehner, S. Coats, and K.A. McKinnon, 2020: The value of initial condition large ensembles to robust adaptation decision-making. *Earth's Future*, **8** (10), e2012EF001610. https://doi.org/10.1029/2020ef001610

292. McKinnon, K.A. and C. Deser, 2021: The inherent uncertainty of precipitation variability, trends, and extremes due to internal variability, with implications for western U.S. water resources. *Journal of Climate*, **34** (24), 9605–9622. https://doi.org/10.1175/jcli-d-21-0251.1

293. Garcia-Menendez, F., E. Monier, and N.E. Selin, 2017: The role of natural variability in projections of climate change impacts on U.S. ozone pollution. *Geophysical Research Letters*, **44** (6), 2911–2921. https://doi.org/10.1002/2016gl071565

294. Saari, R.K., Y. Mei, E. Monier, and F. Garcia-Menendez, 2019: Effect of health-related uncertainty and natural variability on health impacts and cobenefits of climate policy. *Environmental Science & Technology*, **53** (3), 1098–1108. https://doi.org/10.1021/acs.est.8b05094

295. Frölicher, T.L., K.B. Rodgers, C.A. Stock, and W.W.L. Cheung, 2016: Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors. *Global Biogeochemical Cycles*, **30** (8), 1224–1243. https://doi.org/10.1002/2015gb005338

296. Williamson, M.S., C.W. Thackeray, P.M. Cox, A. Hall, C. Huntingford, and F.J.M.M. Nijsse, 2021: Emergent constraints on climate sensitivities. *Reviews of Modern Physics*, **93** (2), 025004. https://doi.org/10.1103/revmodphys.93.025004

297. Herring, S.C., N. Christidis, A. Hoell, M.P. Hoerling, and P.A. Stott, 2020: Explaining extreme events of 2018 from a climate perspective. *Bulletin of the American Meteorological Society*, **101** (1), S1–S140. https://doi.org/10.1175/bams-explainingextremeevents2018.1

298. Herring, S.C., N. Christidis, A. Hoell, M.P. Hoerling, and P.A. Stott, 2021: Explaining extreme events of 2019 from a climate perspective. *Bulletin of the American Meteorological Society*, **102** (1), S1–S115. https://doi.org/10.1175/bams-explainingextremeevents2019.1

299. Herring, S.C., A. Hoell, M.P. Hoerling, J.P. Kossin, C.J. Schreck III, and P.A. Stott, 2016: Explaining extreme events of 2015 from a climate perspective. *Bulletin of the American Meteorological Society*, **97** (12), S1–S145. https://doi.org/10.1175/bams-explainingextremeevents2015.1

300. Herring, S.C., M.P. Hoerling, J.P. Kossin, T.C. Peterson, and P.A. Stott, 2015: Introduction to explaining extreme events of 2014 from a climate perspective. *Bulletin of the American Meteorological Society*, **96** (12), S1–S4. https://doi.org/10.1175/bams-d-15-00157.1

301. Herring, S.C., M.P. Hoerling, T.C. Peterson, and P.A. Stott, 2014: Explaining extreme events of 2013 from a climate perspective. *Bulletin of the American Meteorological Society*, **95** (9), S1–S104. https://doi.org/10.1175/1520-0477-95.9.s1.1

302. Peterson, T.C., M.P. Hoerling, P.A. Stott, and S.C. Herring, 2013: Explaining extreme events of 2012 from a climate perspective. *Bulletin of the American Meteorological Society*, **94** (9), S1–S74. https://doi.org/10.1175/bams-d-13-00085.1

303. Peterson, T.C., P.A. Stott, and S. Herring, 2012: Explaining extreme events of 2011 from a climate perspective. *Bulletin of the American Meteorological Society*, **93** (7), 1041–1067. https://doi.org/10.1175/bams-d-12-00021.1

304. Reed, K.A., M.F. Wehner, A.M. Stansfield, and C.M. Zarzycki, 2021: Anthropogenic influence on Hurricane Dorian's extreme rainfall. *Bulletin of the American Meteorological Society*, **102** (1), S9–S15. https://doi.org/10.1175/bams-d-20-0160.1

305. Menne, M.J., I. Durre, R.S. Vose, B.E. Gleason, and T.G. Houston, 2012: An overview of the Global Historical Climatology Network-Daily database. *Journal of Atmospheric and Oceanic Technology*, **29** (7), 897–910. https://doi.org/10.1175/jtech-d-11-00103.1

306. Pearl, J., 2009: Causal inference in statistics: An overview. *Statistics Surveys*, **3**, 96–146. https://doi.org/10.1214/09-ss057

307. Easterling, D.R., K.E. Kunkel, M.F. Wehner, and L. Sun, 2016: Detection and attribution of climate extremes in the observed record. *Weather and Climate Extremes*, **11**, 17–27. https://doi.org/10.1016/j.wace.2016.01.001

308. Stott, P.A., N. Christidis, F.E.L. Otto, Y. Sun, J.-P. Vanderlinden, G.J. van Oldenborgh, R. Vautard, H. von Storch, P. Walton, P. Yiou, and F.W. Zwiers, 2016: Attribution of extreme weather and climate-related events. *WIREs Climate Change*, **7** (1), 23–41. https://doi.org/10.1002/wcc.380

309. Granger, C.W.J., 1969: Investigating causal relations by econometric models and cross-spectral methods. *Econometrica*, **37** (3), 424–438. https://doi.org/10.2307/1912791

310. Richey, A.S., B.F. Thomas, M.-H. Lo, J.T. Reager, J.S. Famiglietti, K. Voss, S. Swenson, and M. Rodell, 2015: Quantifying renewable groundwater stress with GRACE. *Water Resources Research*, **51** (7), 5217–5238. https://doi.org/10.1002/2015wr017349

311. Cheng, L., K.E. Trenberth, J. Fasullo, T. Boyer, J. Abraham, and J. Zhu, 2017: Improved estimates of ocean heat content from 1960 to 2015. *Science Advances*, **3** (3), e1601545. https://doi.org/10.1126/sciadv.1601545

312. Guo, Y., E.K.M. Chang, and S.S. Leroy, 2009: How strong are the Southern Hemisphere storm tracks? *Geophysical Research Letters*, **36** (22). https://doi.org/10.1029/2009gl040733

313. Hock, R., G. Rasul, C. Adler, B. Cáceres, S. Gruber, Y. Hirabayashi, M. Jackson, A. Kääb, S. Kang, S. Kutuzov, A. Milner, U. Molau, S. Morin, B. Orlove, and H. Steltzer, 2019: Ch. 2. High mountain areas. In: *The Ocean and Cryosphere in a Changing Climate*. Pörtner, H.O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds. Cambridge University Press, Cambridge, UK, 131–202. https://doi.org/10.1017/9781009157964.004

314. Thornton, J.M., R. Therrien, G. Mariéthoz, N. Linde, and P. Brunner, 2022: Simulating fully-integrated hydrological dynamics in complex alpine headwaters: Potential and challenges. *Water Resources Research*, **58** (4), e2020WR029390. https://doi.org/10.1029/2020wr029390

315. Scaife, A.A. and D. Smith, 2018: A signal-to-noise paradox in climate science. *npj Climate and Atmospheric Science*, **1** (1), 28. https://doi.org/10.1038/s41612-018-0038-4

316. Hallam, S., G.D. McCarthy, X. Feng, S.A. Josey, E. Harris, A. Düsterhus, S. Ogungbenro, and J.J.M. Hirschi, 2023: The relationship between sea surface temperature anomalies, wind and translation speed and North Atlantic tropical cyclone rainfall over ocean and land. *Environmental Research Communications*, **5** (2), 025007. https://doi.org/10.1088/2515-7620/acb31c

317. Deser, C., 2020: Certain uncertainty: The role of internal climate variability in projections of regional climate change and risk management. *Earth's Future*, **8** (12), e2020EF001854. https://doi.org/10.1029/2020ef001854

318. Lee, J.-Y., J. Marotzke, G. Bala, L. Cao, S. Corti, J.P. Dunne, F. Engelbrecht, E. Fischer, J.C. Fyfe, C. Jones, A. Maycock, J. Mutemi, O. Ndiaye, S. Panickal, and T. Zhou, 2021: Ch. 4. Future global climate: Scenario-based projections and nearterm information. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 553–672. https://doi.org/10.1017/9781009157896.006

319. Shaw, T.A. and A. Voigt, 2015: Tug of war on summertime circulation between radiative forcing and sea surface warming. *Nature Geoscience*, **8** (7), 560–566. https://doi.org/10.1038/ngeo2449

320. Chang, E.K.M., Y. Guo, and X. Xia, 2012: CMIP5 multimodel ensemble projection of storm track change under global warming. *Journal of Geophysical Research: Atmospheres*, **117** (D23). https://doi.org/10.1029/2012jd018578

321. Colle, B.A., J.F. Booth, and E.K.M. Chang, 2015: A review of historical and future changes of extratropical cyclones and associated impacts along the US East Coast. *Current Climate Change Reports*, **1** (3), 125–143. https://doi.org/10.1007/s40641-015-0013-7

322. Li, W., L. Li, M. Ting, and Y. Liu, 2012: Intensification of Northern Hemisphere subtropical highs in a warming climate. *Nature Geoscience*, **5** (11), 830–834. https://doi.org/10.1038/ngeo1590

323. Knutson, T.R. and J. Ploshay, 2021: Sea level pressure trends: Model-based assessment of detection, attribution, and consistency with CMIP5 historical simulations. *Journal of Climate*, **34** (1), 327–346. https://doi.org/10.1175/jcli-d-19-0997.1

324. Allan, R.P., M. Barlow, M.P. Byrne, A. Cherchi, H. Douville, H.J. Fowler, T.Y. Gan, A.G. Pendergrass, D. Rosenfeld, A.L.S. Swann, L.J. Wilcox, and O. Zolina, 2020: Advances in understanding large-scale responses of the water cycle to climate change. *Annals of the New York Academy of Sciences*, **1472** (1), 49–75. https://doi.org/10.1111/nyas.14337

325. Romps, D.M., 2014: An analytical model for tropical relative humidity. *Journal of Climate*, **27** (19), 7432–7449. https://doi.org/10.1175/jcli-d-14-00255.1

326. Byrne, M.P. and P.A. O'Gorman, 2015: The response of precipitation minus evapotranspiration to climate warming: Why the "wet-get-wetter, dry-get-drier" scaling does not hold over land. *Journal of Climate*, **28** (20), 8078–8092. https://doi.org/10.1175/jcli-d-15-0369.1

327. Friedlingstein, P., M. O'Sullivan, M.W. Jones, R.M. Andrew, J. Hauck, A. Olsen, G.P. Peters, W. Peters, J. Pongratz, S. Sitch, C. Le Quéré, J.G. Canadell, P. Ciais, R.B. Jackson, S. Alin, L.E.O.C. Aragão, A. Arneth, V. Arora, N.R. Bates, M. Becker, A. Benoit-Cattin, H.C. Bittig, L. Bopp, S. Bultan, N. Chandra, F. Chevallier, L.P. Chini, W. Evans, L. Florentie, P.M. Forster, T. Gasser, M. Gehlen, D. Gilfillan, T. Gkritzalis, L. Gregor, N. Gruber, I. Harris, K. Hartung, V. Haverd, R.A. Houghton, T. Ilyina, A.K. Jain, E. Joetzjer, K. Kadono, E. Kato, V. Kitidis, J.I. Korsbakken, P. Landschützer, N. Lefèvre, A. Lenton, S. Lienert, Z. Liu, D. Lombardozzi, G. Marland, N. Metzl, D.R. Munro, J.E.M.S. Nabel, S.I. Nakaoka, Y. Niwa, K. O'Brien, T. Ono, P.I. Palmer, D. Pierrot, B. Poulter, L. Resplandy, E. Robertson, C. Rödenbeck, J. Schwinger, R. Séférian, I. Skjelvan, A.J.P. Smith, A.J. Sutton, T. Tanhua, P.P. Tans, H. Tian, B. Tilbrook, G. van der Werf, N. Vuichard, A.P. Walker, R. Wanninkhof, A.J. Watson, D. Willis, A.J. Wiltshire, W. Yuan, X. Yue, and S. Zaehle, 2020: Global carbon budget 2020. *Earth System Science Data*, **12** (4), 3269–3340. https://doi.org/10.5194/essd-12-3269-2020

328. Rödenbeck, C., D.C.E. Bakker, N. Gruber, Y. Iida, A.R. Jacobson, S. Jones, P. Landschützer, N. Metzl, S. Nakaoka, A. Olsen, G.H. Park, P. Peylin, K.B. Rodgers, T.P. Sasse, U. Schuster, J.D. Shutler, V. Valsala, R. Wanninkhof, and J. Zeng, 2015: Data-based estimates of the ocean carbon sink variability—First results of the Surface Ocean $pCO_2$ Mapping intercomparison (SOCOM). *Biogeosciences*, **12** (23), 7251–7278. https://doi.org/10.5194/bg-12-7251-2015

329. Takahashi, T., S.C. Sutherland, R. Wanninkhof, C. Sweeney, R.A. Feely, D.W. Chipman, B. Hales, G. Friederich, F. Chavez, C. Sabine, A. Watson, D.C.E. Bakker, U. Schuster, N. Metzl, H. Yoshikawa-Inoue, M. Ishii, T. Midorikawa, Y. Nojiri, A. Körtzinger, T. Steinhoff, M. Hoppema, J. Olafsson, T.S. Arnarson, B. Tilbrook, T. Johannessen, A. Olsen, R. Bellerby, C.S. Wong, B. Delille, N.R. Bates, and H.J.W. de Baar, 2009: Climatological mean and decadal change in surface ocean $pCO_2$, and net sea–air $CO_2$ flux over the global oceans. *Deep Sea Research Part II: Topical Studies in Oceanography*, **56** (8), 554–577. https://doi.org/10.1016/j.dsr2.2008.12.009

330. Baldocchi, D.D., T.A. Black, P.S. Curtis, E. Falge, J.D. Fuentes, A. Granier, L. Gu, A. Knohl, K. Pilegaard, H.P. Schmid, R. Valentini, K. Wilson, S. Wofsy, L. Xu, and S. Yamamoto, 2005: Predicting the onset of net carbon uptake by deciduous forests with soil temperature and climate data: A synthesis of FLUXNET data. *International Journal of Biometeorology*, **49** (6), 377–387. https://doi.org/10.1007/s00484-005-0256-4

331. Wouters, B. and R.S.W. van de Wal, 2018: Global sea-level budget 1993–present. *Earth System Science Data*, **10** (3), 1551–1590. https://doi.org/10.5194/essd-10-1551-2018

332. Frederikse, T., K. Simon, C.A. Katsman, and R. Riva, 2017: The sea-level budget along the Northwest Atlantic coast: GIA, mass changes, and large-scale ocean dynamics. *Journal of Geophysical Research: Oceans*, **122** (7), 5486–5501. https://doi.org/10.1002/2017jc012699

333. Harvey, T.C., B.D. Hamlington, T. Frederikse, R.S. Nerem, C.G. Piecuch, W.C. Hammond, G. Blewitt, P.R. Thompson, D.P.S. Bekaert, F.W. Landerer, J.T. Reager, R.E. Kopp, H. Chandanpurkar, I. Fenty, D. Trossman, J.S. Walker, and C. Boening, 2021: Ocean mass, sterodynamic effects, and vertical land motion largely explain US coast relative sea level rise. *Communications Earth & Environment*, **2** (1), 233. https://doi.org/10.1038/s43247-021-00300-w

334. Rietbroek, R., S.-E. Brunnabend, J. Kusche, J. Schröter, and C. Dahle, 2016: Revisiting the contemporary sea-level budget on global and regional scales. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (6), 1504–1509. https://doi.org/10.1073/pnas.1519132113

335. IPCC, 1990: *Climate Change: The IPCC 1990 and 1992 Assessment*. Houghton, J.T., G.J. Jenkins, and J.J. Ephraums, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 178 pp. https://www.ipcc.ch/report/climate-change-the-ipcc-1990-and-1992-assessments/

336. National Research Council, 1979: *Carbon Dioxide and Climate: A Scientific Assessment*. The National Academies Press, Washington, DC, 34 pp. https://doi.org/10.17226/12181

337. Cohen, J., X. Zhang, J. Francis, T. Jung, R. Kwok, J. Overland, T.J. Ballinger, U.S. Bhatt, H.W. Chen, D. Coumou, S. Feldstein, H. Gu, D. Handorf, G. Henderson, M. Ionita, M. Kretschmer, F. Laliberte, S. Lee, H.W. Linderholm, W. Maslowski, Y. Peings, K. Pfeiffer, I. Rigor, T. Semmler, J. Stroeve, P.C. Taylor, S. Vavrus, T. Vihma, S. Wang, M. Wendisch, Y. Wu, and J. Yoon, 2020: Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather. *Nature Climate Change*, **10** (1), 20–29. https://doi.org/10.1038/s41558-019-0662-y

338. Doblas-Reyes, F.J., A.A. Sörensson, M. Almazroui, A. Dosio, W.J. Gutowski, R. Haarsma, R. Hamdi, B. Hewitson, W.-T. Kwon, B.L. Lamptey, D. Maraun, T.S. Stephenson, I. Takayabu, L. Terray, A. Turner, and Z. Zuo, 2021: Ch. 10. Linking global to regional climate change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1363–1512. https://doi.org/10.1017/9781009157896.012

339. Neelin, J.D., C. Martinez-Villalobos, S.N. Stechmann, F. Ahmed, G. Chen, J.M. Norris, Y.-H. Kuo, and G. Lenderink, 2022: Precipitation extremes and water vapor. *Current Climate Change Reports*, **8** (1), 17–33. https://doi.org/10.1007/s40641-021-00177-z

340. Swann, A.L.S., F.M. Hoffman, C.D. Koven, and J.T. Randerson, 2016: Plant responses to increasing $CO_2$ reduce estimates of climate impacts on drought severity. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (36), 10019–10024. https://doi.org/10.1073/pnas.1604581113

341. Ukkola, A.M., I.C. Prentice, T.F. Keenan, A.I.J.M. van Dijk, N.R. Viney, Ranga B. Myneni, and J. Bi, 2016: Reduced streamflow in water-stressed climates consistent with $CO_2$ effects on vegetation. *Nature Climate Change*, **6** (1), 75–78. https://doi.org/10.1038/nclimate2831

342. Wang, R., L. Li, P. Gentine, Y. Zhang, J. Chen, X. Chen, L. Chen, L. Ning, L. Yuan, and G. Lü, 2022: Recent increase in the observation-derived land evapotranspiration due to global warming. *Environmental Research Letters*, **17** (2), 024020. https://doi.org/10.1088/1748-9326/ac4291

343. Mankin, J.S., J.E. Smerdon, B.I. Cook, A.P. Williams, and R. Seager, 2017: The curious case of projected twenty-first-century drying but Greening in the American West. *Journal of Climate*, **30** (21), 8689–8710. https://doi.org/10.1175/jcli-d-17-0213.1

344. Jung, M., C. Schwalm, M. Migliavacca, S. Walther, G. Camps-Valls, S. Koirala, P. Anthoni, S. Besnard, P. Bodesheim, N. Carvalhais, F. Chevallier, F. Gans, D.S. Goll, V. Haverd, P. Köhler, K. Ichii, A.K. Jain, J. Liu, D. Lombardozzi, J.E.M.S. Nabel, J.A. Nelson, M. O'Sullivan, M. Pallandt, D. Papale, W. Peters, J. Pongratz, C. Rödenbeck, S. Sitch, G. Tramontana, A. Walker, U. Weber, and M. Reichstein, 2020: Scaling carbon fluxes from eddy covariance sites to globe: Synthesis and evaluation of the FLUXCOM approach. *Biogeosciences*, **17** (5), 1343–1365. https://doi.org/10.5194/bg-17-1343-2020

345. Natali, S.M., J.P. Holdren, B.M. Rogers, R. Treharne, P.B. Duffy, R. Pomerance, and E. MacDonald, 2021: Permafrost carbon feedbacks threaten global climate goals. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (21), e2100163118. https://doi.org/10.1073/pnas.2100163118

346. Shirzaei, M., J. Freymueller, T.E. Törnqvist, D.L. Galloway, T. Dura, and P.S.J. Minderhoud, 2021: Measuring, modelling and projecting coastal land subsidence. *Nature Reviews Earth & Environment*, **2** (1), 40–58. https://doi.org/10.1038/s43017-020-00115-x

347. Seneviratne, S.I., T. Corti, E.L. Davin, M. Hirschi, E.B. Jaeger, I. Lehner, B. Orlowsky, and A.J. Teuling, 2010: Investigating soil moisture—Climate interactions in a changing climate: A review. *Earth-Science Reviews*, **99** (3–4), 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004

348. Miralles, D.G., P. Gentine, S.I. Seneviratne, and A.J. Teuling, 2019: Land–atmospheric feedbacks during droughts and heatwaves: State of the science and current challenges. *Annals of the New York Academy of Sciences*, **1436** (1), 19–35. https://doi.org/10.1111/nyas.13912

349. Zhou, D., J. Xiao, S. Frolking, L. Zhang, and G. Zhou, 2022: Urbanization contributes little to global warming but substantially intensifies local and regional land surface warming. *Earth's Future*, **10** (5), e2021EF002401. https://doi.org/10.1029/2021ef002401

350. Merz, B., G. Blöschl, S. Vorogushyn, F. Dottori, J.C.J.H. Aerts, P. Bates, M. Bertola, M. Kemter, H. Kreibich, U. Lall, and E. Macdonald, 2021: Causes, impacts and patterns of disastrous river floods. *Nature Reviews Earth & Environment*, **2** (9), 592–609. https://doi.org/10.1038/s43017-021-00195-3

351. Schröter, K., M. Kunz, F. Elmer, B. Mühr, and B. Merz, 2015: What made the June 2013 flood in Germany an exceptional event? A hydro-meteorological evaluation. *Hydrology and Earth System Sciences*, **19** (1), 309–327. https://doi.org/10.5194/hess-19-309-2015

352. Fisher, R.A. and C.D. Koven, 2020: Perspectives on the future of land surface models and the challenges of representing complex terrestrial systems. *Journal of Advances in Modeling Earth Systems*, **12** (4), e2018MS001453. https://doi.org/10.1029/2018ms001453

353. Coumou, D., G. Di Capua, S. Vavrus, L. Wang, and S. Wang, 2018: The influence of Arctic amplification on mid-latitude summer circulation. *Nature Communications*, **9** (1), 2959. https://doi.org/10.1038/s41467-018-05256-8

354. Osman, M.B., S. Coats, S.B. Das, J.R. McConnell, and N. Chellman, 2021: North Atlantic jet stream projections in the context of the past 1,250 years. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (38), e2104105118. https://doi.org/10.1073/pnas.2104105118

355. Overland, J.E., 2021: Causes of the record-breaking Pacific Northwest heatwave, late June 2021. *Atmosphere*, **12** (11), 1434. https://doi.org/10.3390/atmos12111434

356. Perkins-Kirkpatrick, S.E. and S.C. Lewis, 2020: Increasing trends in regional heatwaves. *Nature Communications*, **11** (1), 3357. https://doi.org/10.1038/s41467-020-16970-7

357. Kunkel, K.E., T.R. Karl, H. Brooks, J. Kossin, J. Lawrimore, D. Arndt, L. Bosart, D. Changnon, S.L. Cutter, N. Doesken, K. Emanuel, P.Y. Groisman, R.W. Katz, T. Knutson, J. O'Brien, C.J. Paciorek, T.C. Peterson, K. Redmond, D. Robinson, J. Trapp, R. Vose, S. Weaver, M. Wehner, K. Wolter, and D. Wuebbles, 2013: Monitoring and understanding trends in extreme storms: State of knowledge. *Bulletin of the American Meteorological Society*, **94** (4), 499–514. https://doi.org/10.1175/bams-d-11-00262.1

358. Vousdoukas, M.I., L. Mentaschi, E. Voukouvalas, M. Verlaan, S. Jevrejeva, L.P. Jackson, and L. Feyen, 2018: Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nature Communications*, **9** (1), 2360. https://doi.org/10.1038/s41467-018-04692-w

359. Gudmundsson, L. and S. Seneviratne, 2016: Anthropogenic climate change affects meteorological drought risk in Europe. *Environmental Research Letters*, **11**, 044005. https://doi.org/10.1088/1748-9326/11/4/044005

360. Kelley, C.P., S. Mohtadi, M.A. Cane, R. Seager, and Y. Kushnir, 2015: Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (11), 3241–3246. https://doi.org/10.1073/pnas.1421533112

361. Otto, F., P. Wolski, F. Lehner, C. Tebaldi, G.J. Van Oldenborgh, S. Hogesteeger, R. Singh, P. Holden, N. Fuckar, R. Odoulami, and M. New, 2018: Anthropogenic influence on the drivers of the Western Cape drought 2015–2017. *Environmental Research Letters*, **13**, 124010. https://doi.org/10.1088/1748-9326/aae9f9

362. Seager, R., T.J. Osborn, Y. Kushnir, I.R. Simpson, J. Nakamura, and H. Liu, 2019: Climate variability and change of Mediterranean-type climates. *Journal of Climate*, **32** (10), 2887–2915. https://doi.org/10.1175/jcli-d-18-0472.1

363. Abram, N.J., B.J. Henley, A. Sen Gupta, T.J.R. Lippmann, H. Clarke, A.J. Dowdy, J.J. Sharples, R.H. Nolan, T. Zhang, M.J. Wooster, J.B. Wurtzel, K.J. Meissner, A.J. Pitman, A.M. Ukkola, B.P. Murphy, N.J. Tapper, and M.M. Boer, 2021: Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment*, **2** (1), 8. https://doi.org/10.1038/s43247-020-00065-8

364. Andela, N., D.C. Morton, L. Giglio, Y. Chen, G.R. van der Werf, P.S. Kasibhatla, R.S. DeFries, G.J. Collatz, S. Hantson, S. Kloster, D. Bachelet, M. Forrest, G. Lasslop, F. Li, S. Mangeon, J.R. Melton, C. Yue, and J.T. Randerson, 2017: A human-driven decline in global burned area. *Science*, **356** (6345), 1356–1362. https://doi.org/10.1126/science.aal4108

Fifth National Climate Assessment: Chapter 4

# Water

# Chapter 4. Water

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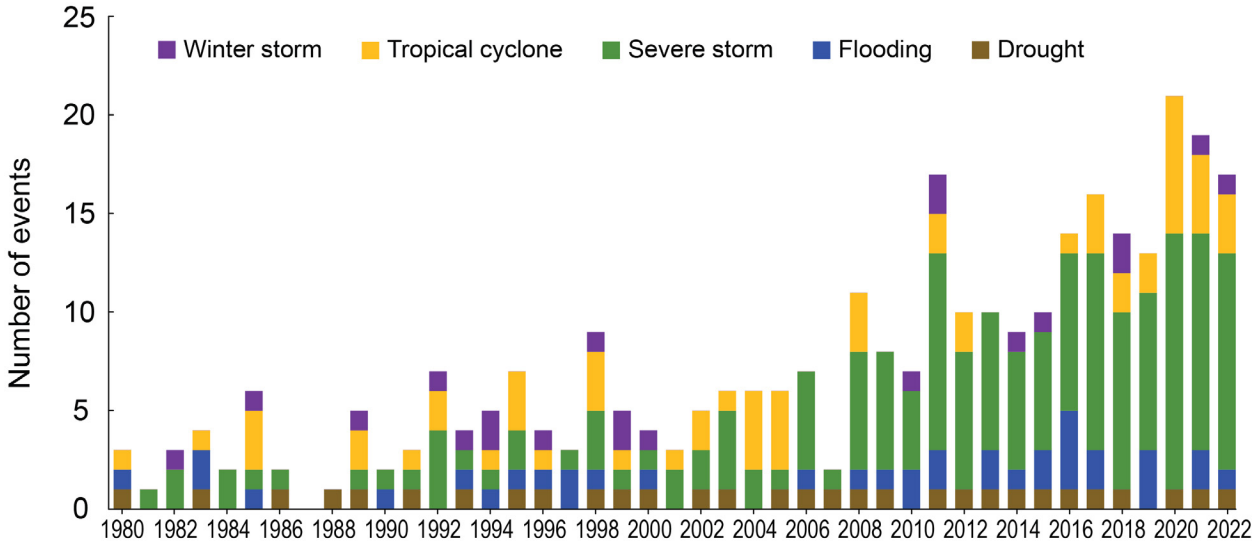
# Introduction

Climate change is intensifying rainfall and floods, deepening droughts, and shifting weather patterns across the globe,[1] causing profound effects on terrestrial freshwater supplies and quality. Rising sea levels, reduced snowpacks, shrinking rivers, and declining groundwater threaten cities and rural communities and endanger forest, riverine, and other ecosystems across the United States.

Climate change, combined with greater exposure and vulnerability, is increasing the frequency of water-related disasters in the US (Figure 4.1).

### Water-Related Billion-Dollar Disasters in the United States

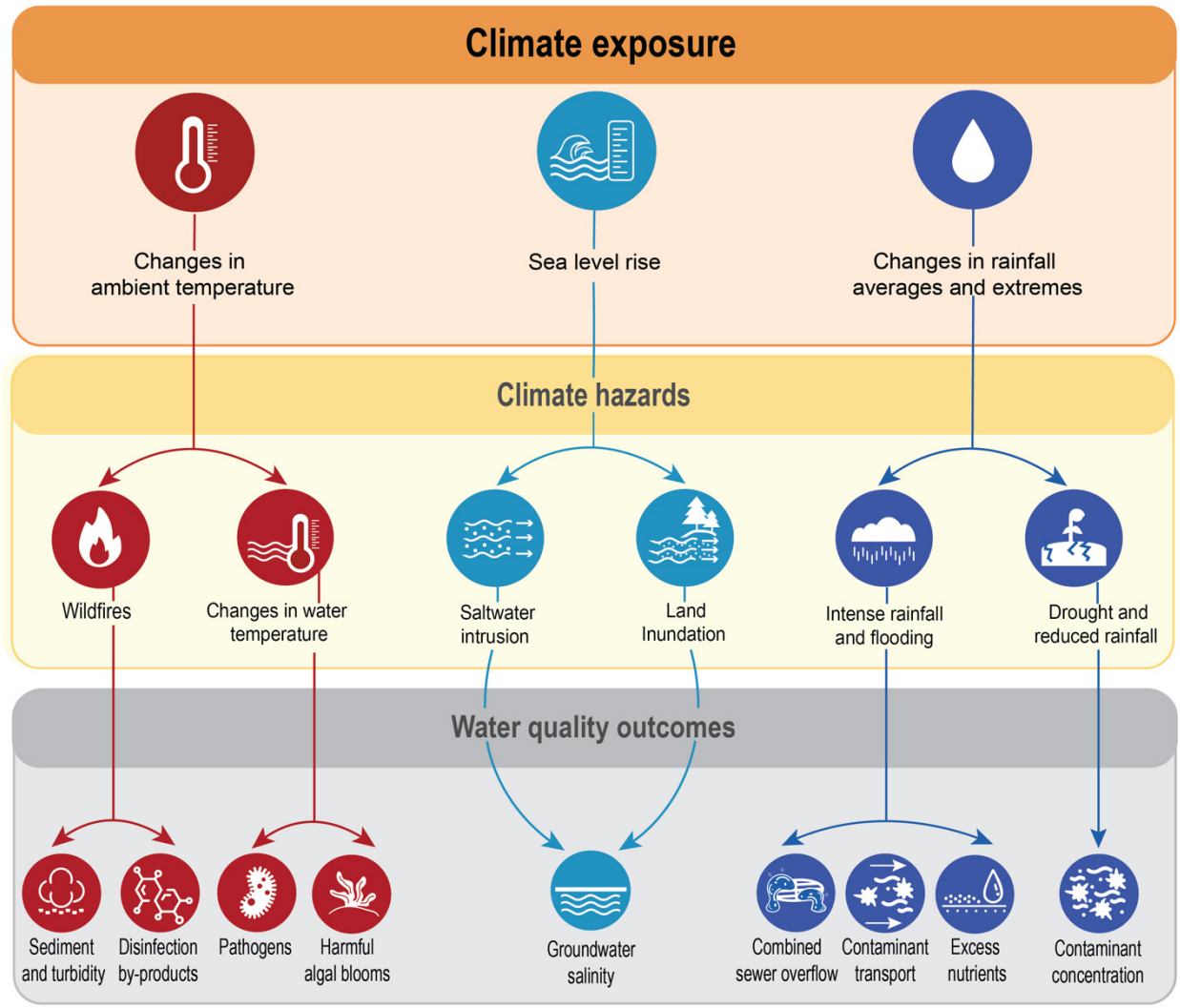



**Water-related billion-dollar disasters are increasing in the United States.**

**Figure 4.1.** Across the US, the number of water-related disasters with damages exceeding $1 billion (adjusted for inflation) during 1980–2022 rose due to increases in exposure, or assets at risk; vulnerability, or how much damage a hazard of a given intensity causes; and climate change-driven increases in the frequency of extremes. Adapted from NCEI 2023.[2]

While these events are primarily related to water *quantity*, impacts related to water *quality* are increasing as well, as predicted in the Fourth National Climate Assessment, released in 2018 (NCA4).[3] Temperature increases, sea level rise, and changes in precipitation are expected to continue to degrade water quality for people and ecosystems (Figure 4.2; KMs 4.2, 15.1, 15.2).[4,5,6]

## Climate Change Impacts to Water Quality




**Climate change threatens the quality of freshwater supplies.**

**Figure 4.2.** Changes in ambient temperature, sea level, and rainfall (**top**) can create climate-related hazards, such as changes in water temperature and saltwater intrusion (**middle**) that can have negative impacts on water quality (**bottom**). Saltwater intrusion is an imminent threat to coastal and island communities dependent on groundwater for drinking water (KMs 30.1, 9.2); agricultural areas face risks to water supplies when fertilizers and pesticides are mobilized by flooding;[7] higher temperatures are putting many areas at risk of exposure to harmful algal blooms (e.g., KM 22.2) and increases in fecal coliform bacteria;[6] and treatment plants are challenged by sediments and debris from wildfires in their source waters (KM 6.1).[8,9] Adapted from Nijhawan and Howard 2022[6] [CC BY 4.0].

Climate change is forcing a reexamination of our concepts of rare events. Extreme precipitation incidents are more intense and more frequent (KM 2.2); extended droughts in the West appear to be due in part to long-term aridification in addition to episodic drying (KM 4.2); and compound hazards are increasing as the events that combine to create them become more frequent (Focus on Compound Events).

The US is slowly adapting to these changes. Utilities are exploring ways to integrate change into planning, and communities are cooperatively seeking solutions to water shortages and flooding (KM 4.3). But barriers arise from legal and regulatory institutions that have been in place for decades or even centuries, locking in practices that hinder adaptation (KM 4.3). The Nation's aging water infrastructure, designed under

regulations and standards appropriate to an unchanging climate, is deteriorating and threatening public health, a situation little changed since it was highlighted in NCA4 (KM 4.2).[3]

Perhaps the most notable advance in recent years is the growing recognition of environmental injustices exacerbated by climate change (KM 1.2). Overburdened populations, including Black, Hispanic, Indigenous, Tribal and other communities, are suffering disproportionate impacts from climate-driven water quality and quantity hazards that threaten these communities' water security (KMs 4.2, 15.1, 15.2, 16.1).

The Nation is making some progress. The tools and data needed to support water resources planning and management have become more sophisticated and widely available, though gaps remain, particularly hydrologic projections for the US Caribbean, Hawai'i, and the US-Affiliated Pacific Islands, where water security concerns are high (KM 4.1; Box 23.2). Gaps in local projections of extreme event frequencies, magnitudes, and durations also hinder adaptation. There has been enormous growth in the availability of science-based climate information for water providers and natural resource managers, demonstrating increasing awareness and demand for solutions. These and similar efforts are the first steps toward building resilient human and natural systems in the face of climate-induced changes to the water cycle.

## Key Message 4.1

## Climate Change Will Continue to Cause Profound Changes in the Water Cycle

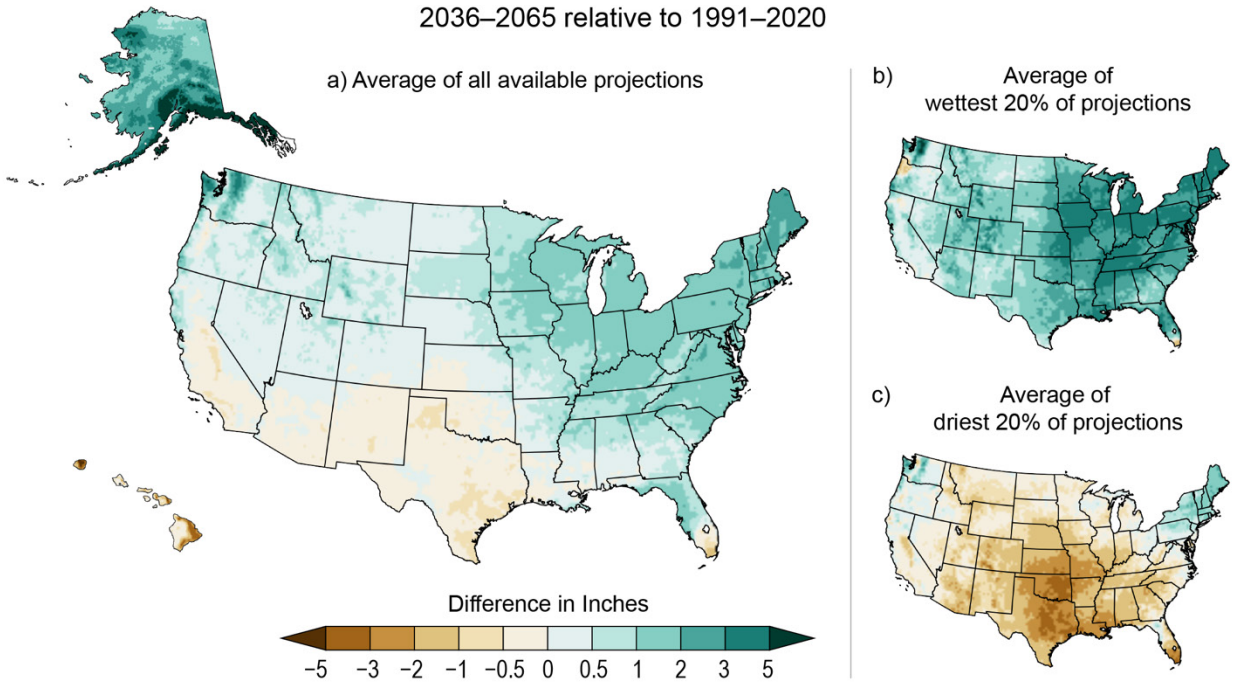
Changes to the water cycle pose risks to people and nature. Alaska and northern and eastern regions of the US are seeing and expect to see more precipitation on average, while the Caribbean, Hawai'i, and southwestern regions of the US are seeing and expect to see less precipitation (*medium confidence*). Heavier rainfall events are expected to increase across the Nation (*very likely*, *very high confidence*), and warming will increase evaporation and plant water use where moisture is not a limiting factor (*medium confidence*). Groundwater supplies are also threatened by warming temperatures that are expected to increase demand (*very likely*, *high confidence*). Snow cover will decrease and melt earlier (*very likely*, *high confidence*). Increasing aridity, declining groundwater levels, declining snow cover, and drought threaten freshwater supplies (*medium confidence*).

Freshwater availability is affected by the quantity of water in storage, the timing of water movement, how much water is used, and its quality,[10] all of which are governed by the interrelated hydrologic components of the water cycle. Changes to these components are occurring across the Nation as a result of human activities as well as human-caused climate change. These changes are superimposed on natural variability, resulting in changes to both water availability and water-related hazards (KMs 2.1, 2.2).

### *Precipitation Changes*

Climate change has already shifted precipitation patterns across the country, including increased variability and elevated likelihood of extreme rainfall events (KMs 2.2, 3.5). These trends exhibit substantial regional and seasonal variations (KM 2.2).[11] Projected changes in annual precipitation also exhibit large regional differences (Figure 4.3). Precipitation trends and projections are discussed in more depth in Chapters 2 and 3.

## Projected Changes in Annual Precipitation by Midcentury



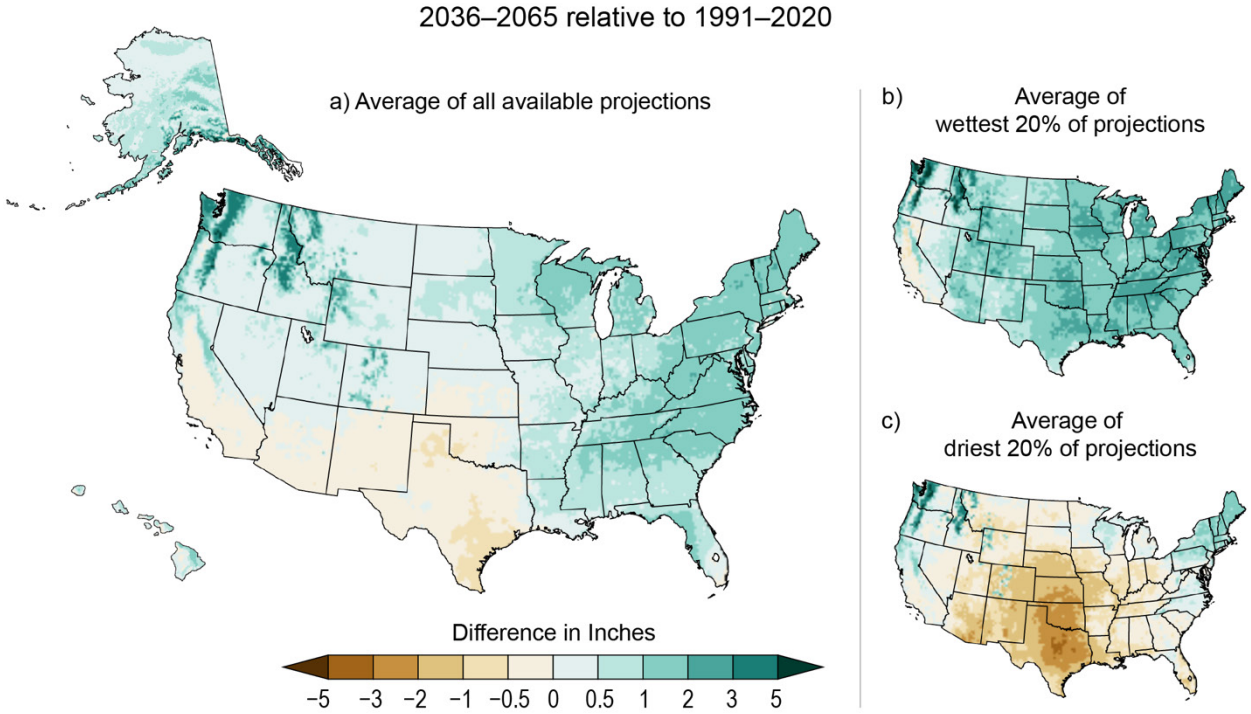

**Annual precipitation projections show large regional differences.**

**Figure 4.3.** Under an intermediate (RCP4.5) scenario, annual precipitation is projected to increase for much of the US (**a**), except for the Southwest, Hawai'i, and the US Caribbean (not shown; see Figure 23.2, which shows rainfall reductions of about 10% by midcentury, and increases in dry days during the wet season, for Puerto Rico). The wettest and driest 20% of projections (**b**, **c**) illustrate the range of uncertainty in annual precipitation projections. This figure shows projected changes in inches. In the Southwest, a half-inch change in annual precipitation has more influence on the region's hydrology than does a half-inch change in the Northeast (see Figure 2.10 for percent changes under different warming levels). Projections are not available for the US-Affiliated Pacific Islands. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

## *Evapotranspiration Changes*

Evapotranspiration is water that evaporates from soil, snow, and surface water or transpires from plants. It is a key component of the water budget and drives irrigation water demand. Increases in temperature and changes in other climate variables alter the evaporative demand (or potential evapotranspiration). In recent decades, evaporative demand has increased in much of the West, with few apparent trends in the East.[12] Actual evapotranspiration is evaporative demand limited by water availability. In the continental US, actual evapotranspiration has trended lower in the Southwest as water availability has declined, while the East and North show an increase. The greatest increase in actual evapotranspiration has been in the South from eastern Texas to northern Florida.[11,13] These trends are largely projected to continue with climate change (Figure 4.4).

## Projected Changes in Annual Actual Evapotranspiration by Midcentury



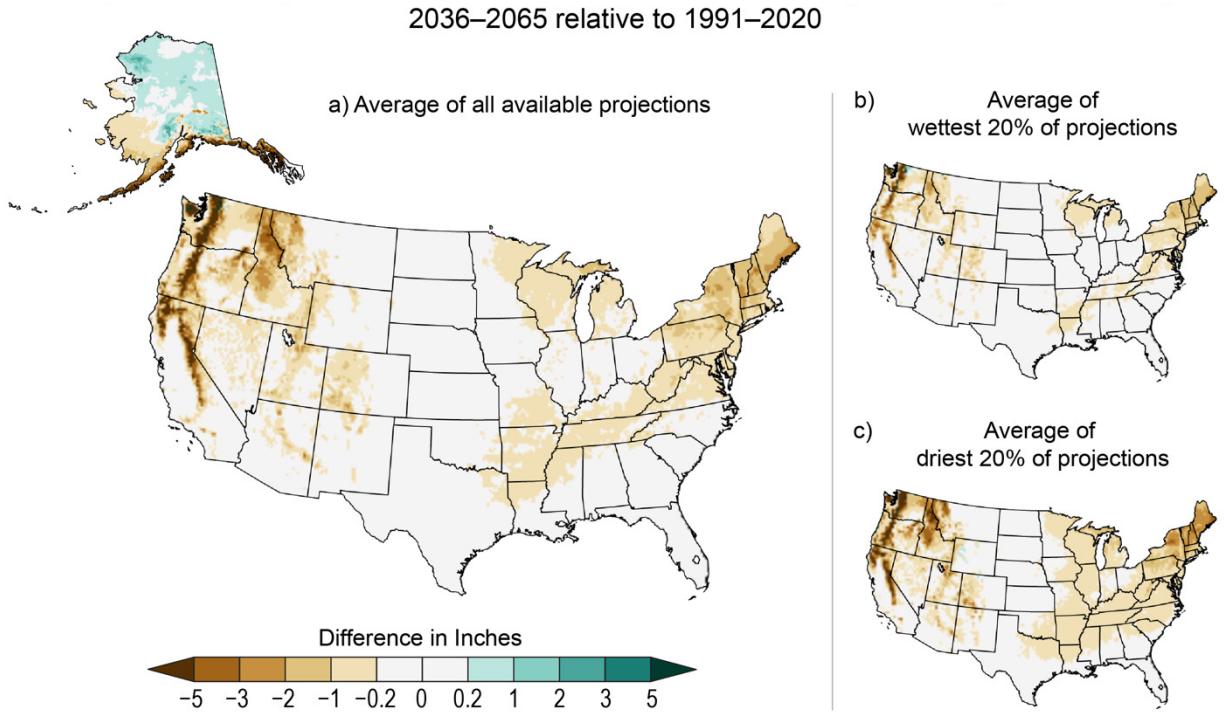

**Actual evapotranspiration is projected to increase across most of the Nation but decrease in the Southern Great Plains and Southwest.**

**Figure 4.4.** Actual evapotranspiration is the water that evaporates from soil and surface water or transpires from plants. Higher rates of evapotranspiration can reduce overall water availability even if precipitation does not change; conversely, low water availability can limit actual evapotranspiration. Under an intermediate scenario (RCP 4.5), actual evapotranspiration is expected to decrease in regions with decreasing or unchanging precipitation (**a**), such as the US Southwest, the Southern Great Plains, and the Caribbean (not shown; Box 23.2). Wetter regions, including the Northwest, Alaska, and the eastern half of the US, will see higher actual evapotranspiration. The wettest and driest projections (**b, c**) illustrate the range of uncertainty. Projections are not available for the US-Affiliated Pacific Islands. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

## *Snow and Glacier Changes*

Snow is a natural reservoir, storing cold-weather precipitation and later releasing water through snowmelt. With higher temperatures, the fraction of precipitation falling as rain instead of snow will increase.[14,15] Warming will also cause earlier snowmelt,[14,16] altered rates of snowmelt and evaporation directly from the snow,[17,18,19,20] and longer snow-free periods.[21,22] Most historical snow-observation records already show trends toward earlier peak snowpack, smaller volumes, and decreasing snow-season duration (Figure A4.7),[11] particularly for warmer maritime and lower-elevation regions.[23,24,25] In areas of the West where snow is the dominant source of runoff,[26] total seasonal snow water volume is projected to decrease by more than 24% by 2050 under intermediate (RCP4.5; Figure 4.5) and higher scenarios, with persistent low-snow conditions emerging within the next 60 years.[24] These snow reductions, combined with projected increases to water demand, are expected to stress water supplies, particularly in the West (KM 28.1), where snowmelt supplies a disproportionate amount of water for municipal water supplies and agriculture.[27,28,29] Reductions in snow cover are also accelerating the retreat of glaciers[30,31,32] that are critical for summer streamflow in Alaska[33] and the Pacific Northwest (Ch. 27).[34]

## Projected Changes in Maximum Annual Snow Water Equivalent by Midcentury




**Continued decreases in snowpack water content are projected across much of the US.**

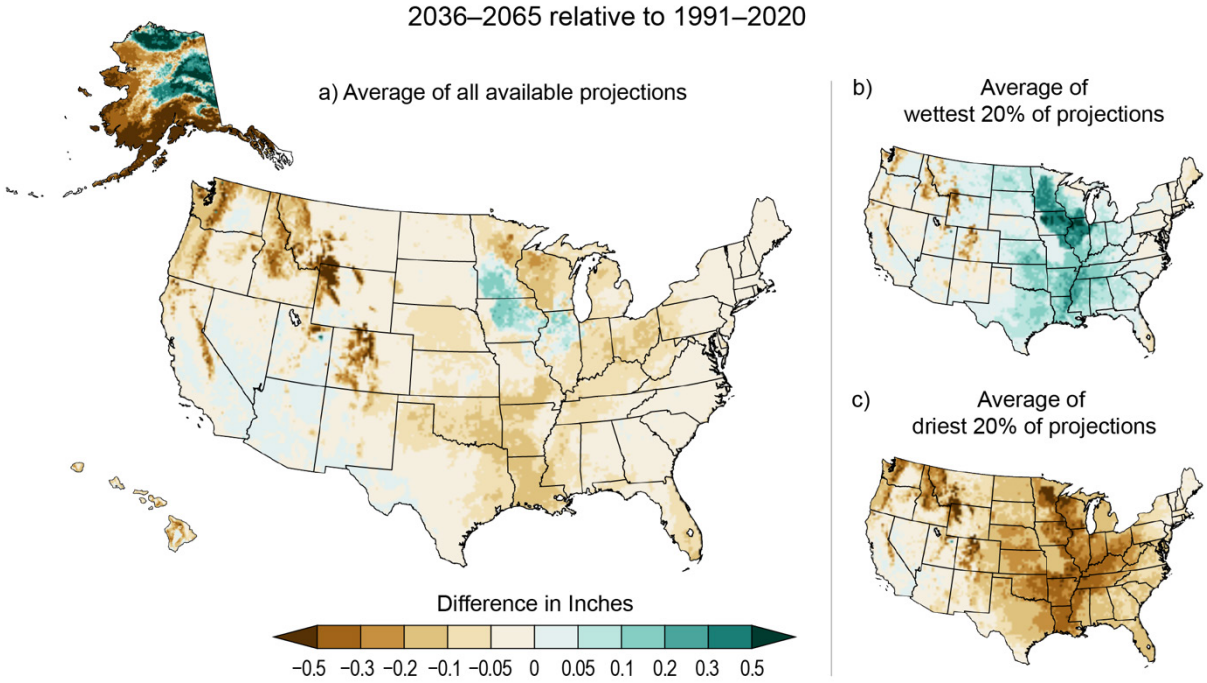
**Figure 4.5.** Snow water equivalent (SWE), the quantity of water stored in the snowpack, is key to regional water supplies. Under an intermediate scenario (RCP 4.5), peak SWE is projected to decline across much of the country except for some high-elevation interior locations in the contiguous United States and parts of Alaska (**a**). The largest snowpack declines are expected in warmer snow climates like coastal southern Alaska and the mountain ranges of California and the Northwest. The wettest (**b**) and driest (**c**) projections both show decreases in SWE, reflecting the influence of warming on future snowpack. Snow on the highest Hawaiian mountain peaks has important cultural and ecological significance, but projections at this resolution are not available. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

## *Soil Moisture Changes*

Soil moisture is water stored in the soil, usually close to the surface. It is a key component of the water cycle, supporting agriculture and ecosystem productivity, modifying streamflow by absorbing precipitation and snowmelt, and modulating climate.[35,36] A scarcity of soil moisture observations[37] has led to uncertainty regarding overall amounts, seasonality, and the direction of changes; however, there is consensus that soils are becoming drier in the Southwest.[38,39,40,41]

Projections suggest that summer soil moisture will decrease across most of the country (Figure 4.6), with parts of the upper Midwest and Alaska[42] as exceptions. The Northwest, parts of the central and eastern US, and Alaska can expect seasonal changes in total soil moisture, with wetter soils in winter.[42,43] Summer soil moisture in the Southwest could increase if summer precipitation is higher, but there is greater confidence in decreasing annual soil moisture in the region (Figure 2.4).[38,43]

### Projected Changes in Average Summer (June–August) Soil Moisture by Midcentury




**Projected decreases in summer soil moisture will have important implications for agriculture and ecosystems.**

**Figure 4.6.** Summer soil moisture supports dryland agriculture and ecosystem functions and reduces irrigation demand and wildfire risk. Under an intermediate scenario (RCP 4.5), soil moisture is projected to decrease during the summer months (June, July, and August) for most of the country (**a**), with the West seeing decreases even under the wettest projections. Exceptions include portions of the Upper Midwest and Alaska. The range between the wettest (**b**) and driest (**c**) projections illustrate the uncertainty in summer soil projections. Projections are not available for the US Caribbean or US-Affiliated Pacific Islands. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

## *Groundwater Changes*

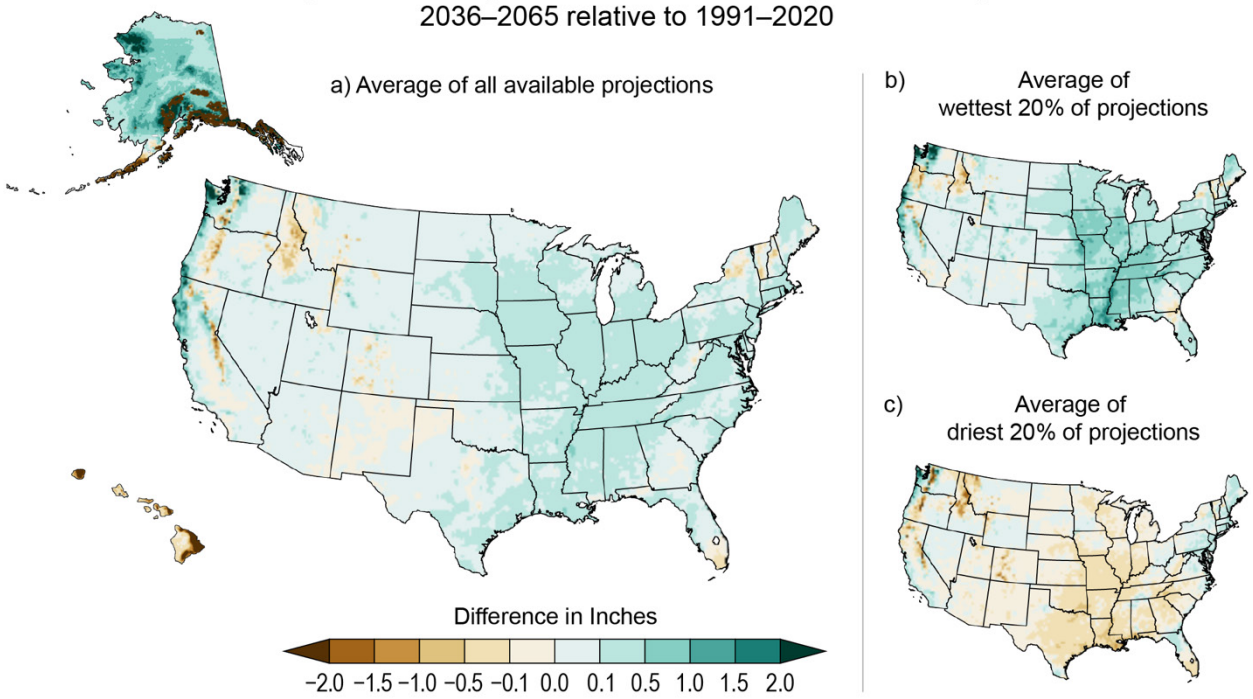
Groundwater is water stored below the land surface; it can be close to the surface or extend hundreds of feet deep. It is a crucial water supply for human systems and can moderate changes in temperature and precipitation.[44,45,46] NCA4 noted that groundwater depletions can increase drought risk and highlighted unsustainable groundwater usage and the likelihood of further declines in the future.[3] More recent work has emphasized the hydrologic connections between surface and groundwater that make surface water systems vulnerable to declining groundwater levels.[47,48]

Groundwater trends vary regionally and are difficult to project because the intensity of both groundwater withdrawals and recharge depends on human factors (e.g., land use, population, surface water allocations, and groundwater regulation) in addition to climate drivers.[49] Natural groundwater recharge varies from year to year but is projected to decrease slightly in the Southwest and increase slightly in the Northwest.[50,51] Higher temperatures will increase irrigation demand (Figure 4.9), which can lead to increased groundwater pumping in areas where groundwater is the primary water supply or where surface water supplies are limited.[52,53,54] Groundwater levels have already been declining in many major aquifers due to lack of management, overpumping, and decreased recharge; increased pumping could accelerate long-term storage losses, but those impacts will depend on the regional factors noted above.[49,52,55,56] Groundwater declines caused by increased drought severity and duration in the future are a concern in many parts of the country (KMs 23.3, 24.5, 28.1; Ch. 26).

## *Runoff Changes*

Changes to the water cycle components discussed above combine with other factors to affect runoff (surface water flow). For example, snowpack changes impact the seasonality of runoff in snowmelt-dominated areas,[57] while soil moisture affects the amount of precipitation and snowmelt that becomes runoff.[58] In addition to direct precipitation and groundwater, runoff is a primary source of water supply for people and ecosystems. Annual runoff trends for the most part have tracked annual precipitation trends. Similarly, the trend toward increasing annual runoff variability in most of the eastern half of the US is consistent with increasing extreme precipitation events there.[11] Increases in heavy precipitation events are projected to increase annual runoff over much of the US (Figure 4.7).[59,60]

### Projected Changes in Annual Runoff by Midcentury



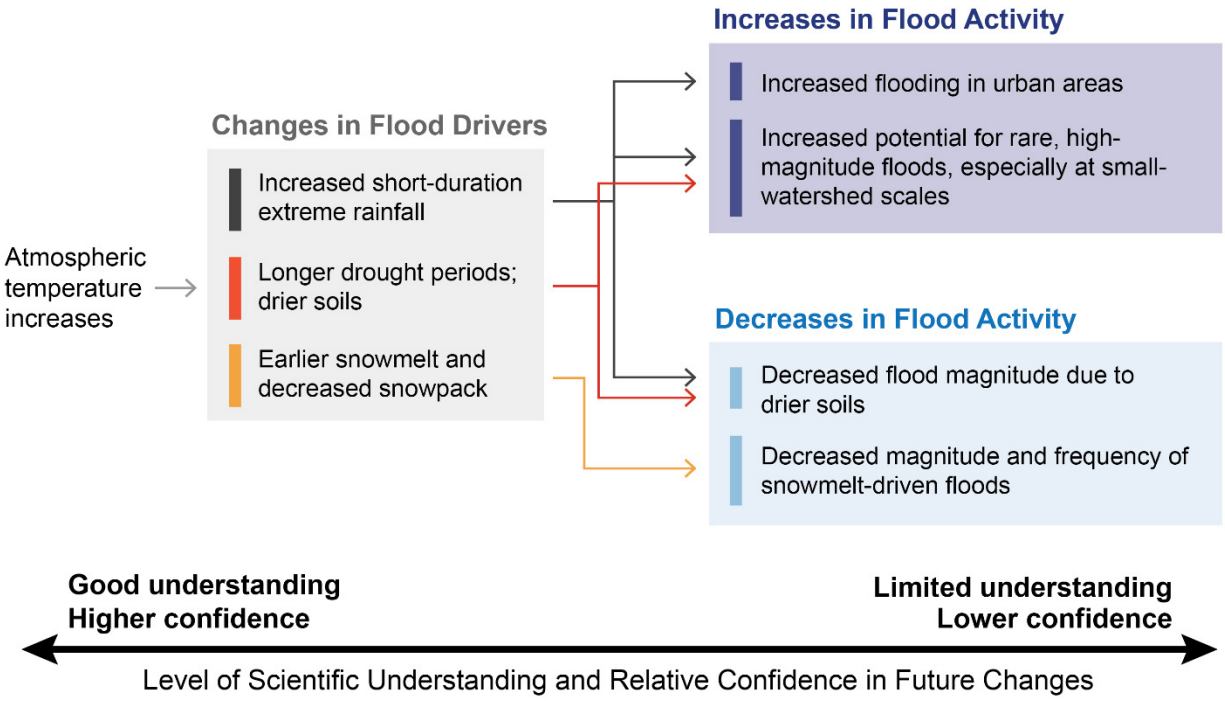

**Projected changes in runoff vary across the Nation due to projected changes in multiple aspects of the water cycle.**

**Figure 4.7.** Rivers and streams aggregate runoff across watersheds, and runoff integrates climate change impacts to the water cycle (Figures 4.3, 4.4, 4.5, 4.6); as a result, impacts to runoff over a watershed are commonly used as surrogates for impacts to streamflow. Under an intermediate scenario (RCP4.5), projections of annual runoff vary geographically depending on relative changes to precipitation, evapotranspiration, snow and ice, groundwater, and soil moisture. Decreases are projected in Hawai'i and parts of the Nation supplied by snow (**a**). Projections are not available for US-Affiliated Pacific Islands or the US Caribbean; however, given projected decreases in precipitation and increases in temperature in the Caribbean, annual runoff is expected to decrease. The range between the wettest (**b**) and driest (**c**) projections illustrate the uncertainty in runoff projections. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

## *Extreme Events: Floods and Droughts*

Inland floods are driven by complex interactions among precipitation amount and timing, soil moisture, snowpack, and land cover (see KM 9.1 for coastal flooding). However, estimates of events such as the 100-year flood typically rely on historical observations and assumptions of an unchanging climate.[61] Methods that account for the added uncertainty of climate change are needed for infrastructure design, land use planning, and other purposes,[62,63,64] but future flood frequency is challenging to predict (Figure 4.8).[65,66] For example, some extreme precipitation events will be buffered by future reductions in soil moisture, which will allow more rainfall to be absorbed,[67,68,69] and some areas are projected to see increases in floods from rain falling on snow,[70,71] precipitation on wildfire-disturbed land,[72,73] and loss of natural water storage in urban landscapes.[74]

### Climate Change Impacts to Inland Flood Drivers and Flood Activity

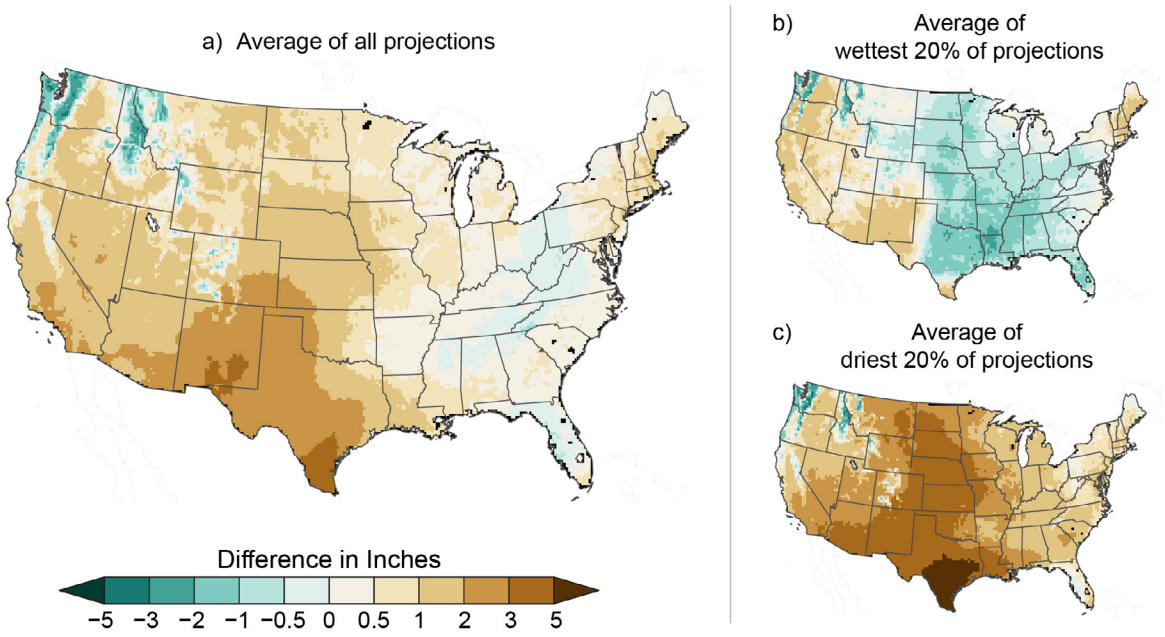



**Climate change may cause both increases and decreases in inland flooding, depending on the location and time of year.**

**Figure 4.8.** Inland floods result from combinations of factors, primarily extreme rainfall, soil moisture, and snowpack and snowmelt conditions. Each of these are subject to substantial variability and change across a wide range of timescales, from daily to decadal, in a warming climate. Scientific confidence in how the climate drivers of flooding will change is higher than in how those drivers will combine to affect floods in particular locations and seasons. Adapted from Yu et al. 2020[66] [CC BY-NC 4.0].

Changes in future precipitation and temperature are expected to exacerbate drought across large portions of the US.[75] Observed trends in drought (Figure A4.9) and climatic water deficit reflect these changes,[13] as do projections, with the strongest drying signal occurring in the Southwest (Figure 4.9).[76]

## Projected Changes in Annual Climatic Water Deficit by Midcentury



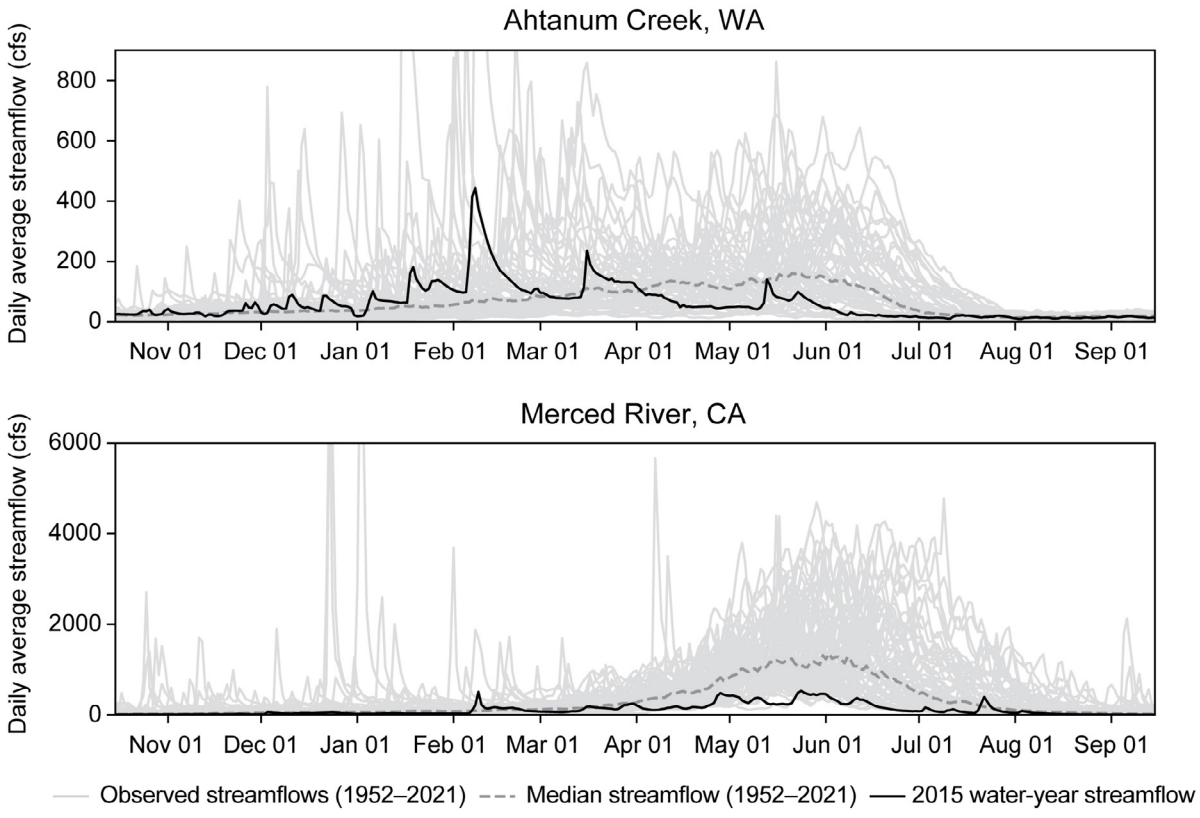

**Water shortages to vegetation will increase across most of the Nation.**

**Figure 4.9.** Climatic water deficit (CWD) is the shortfall of water necessary to fully supply vegetation requirements—CWD is zero if those needs are met, and a higher number indicates drier conditions. Vegetation water needs will increase with increases in temperature; as a result, in the absence of compensating increases in precipitation, CWD is projected to increase. Under an intermediate scenario (RCP4.5), CWD is expected to rise across much of the Nation, with the Great Plains and Southwest seeing the greatest increase (**a**, **c**). Even the wettest projections show increases in CWD in the West (**b**). Projections are not available for the US Caribbean, Alaska, Hawai'i, or US-Affiliated Pacific Islands; however, given expected temperature increases and annual precipitation decreases in Hawai'i and the US Caribbean, CWD is expected to increase in those regions, while Alaska is expected to see both increases and decreases similar to the pattern seen in the Northwest. Figure credit: University of Colorado Boulder.

## Box 4.1. Washington–California 2015 Snow Drought

Snow droughts occurred across much of the western coastal mountain ranges during the 2014/15 winter. However, the climatic causes of these droughts varied. Western Oregon and Washington experienced a *warm* snow drought, wherein wintertime precipitation was 77%–113% of normal but elevated temperatures caused a larger proportion of that precipitation to fall as rain, which reduced snow accumulation and increased winter snowmelt.[15,77] As a result, wintertime streamflows were normal to high, but April to August flows were lower than normal (Figure 4.10).

### Washington–California Snow Drought




**In 2015, parts of Oregon and Washington experienced a warm snow drought while the California Sierra Nevada experienced a dry snow drought.**

**Figure 4.10.** The timelines compare the 70-year (1952–2021) median streamflow (dashed line) with the 2015 water-year (October 2014–September 2015) streamflow (black line). Annual observed streamflows are also shown for 1952–2021 (gray lines). Values are daily average streamflows in cubic feet per second. Streamflow in summer 2015 was abnormally low, resulting from reduced snowpack during a warm snow drought (Ahtanum Creek) and a dry snow drought (Merced River). Daily streamflow is in cubic feet per second for each of the years 1952–2021 (gray lines). Merced River flows are lower year-round because of low total precipitation and little snowfall; Ahtanum Creek flows are shifted from summer to winter in 2014/15 because it was too warm for snow accumulation. Figure credit: University of Maryland, College Park and Lynker.

By contrast, the California Sierra Nevada experienced a *dry* snow drought, resulting in the shallowest snow volume ever recorded there.[15,78,79] Both the dry and warm droughts caused strain on water rights holders. In Oregon and Washington, irrigated crops—including valuable orchard crops—that depend on direct streamflow diversion water rights failed (Figure 4.11), but municipal water supplies that relied on storage rights that allow reservoirs to capture winter runoff were sufficient.[80] In California, total water supply was limited, resulting in severe or complete cutbacks to junior water rights and contract holders.[81]

## Washington Apple Orchard Under Drought Stress

**An apple orchard in the Roza Irrigation District in Washington shows extreme drought stress in September 2015.**

**Figure 4.11.** This apple orchard suffered the effects of a warm snow drought the previous winter. The warm winter temperatures caused much of the precipitation to fall as rain instead of snow, producing a reduced snowpack, and led to early snowmelt, resulting in low streamflows during irrigation season. Photo credit: © Sonia A. Hall.

## Key Message 4.2

### Water Cycle Changes Will Affect All Communities, with Disproportionate Impacts for Some

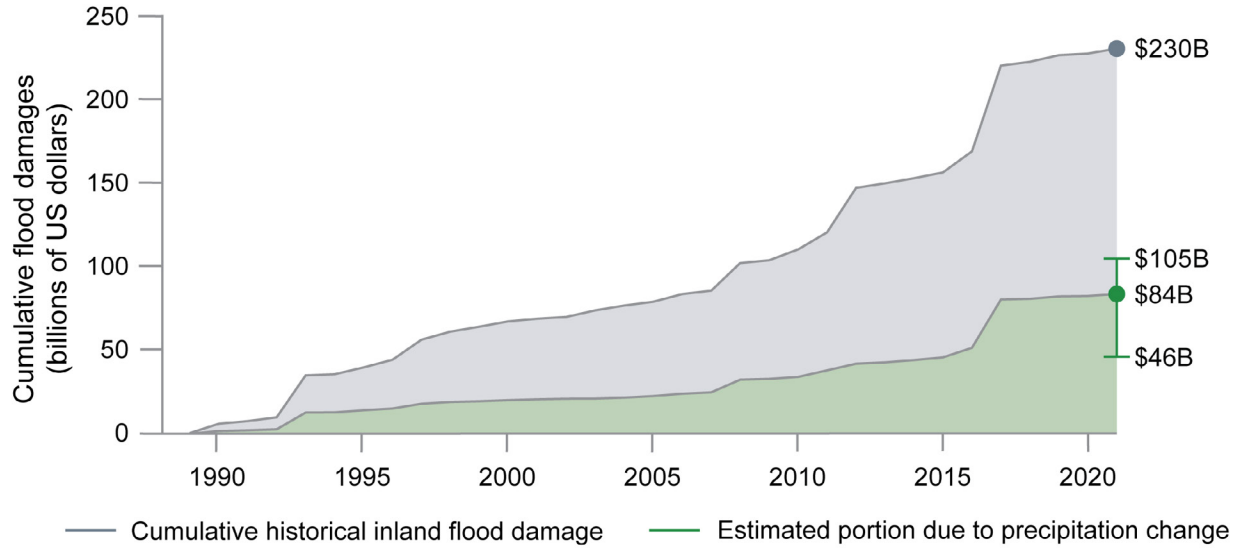
Natural and human systems have evolved under the water cycle's historical patterns, making rapid adaptation challenging. Heavier rainfall, combined with changes in land use and other factors such as soil moisture and snow, is leading to increasing flood damage (*likely, high confidence*). Drought impacts are also increasing (*medium confidence*), as are flood- and drought-related water quality impacts (*medium confidence*). All communities will be affected, but in particular those on the frontline of climate change—including many Black, Hispanic, Tribal, Indigenous, and socioeconomically disadvantaged communities—face growing risks from changes to water quantity and quality due to the proximity of their homes and workplaces to hazards and limited access to resources and infrastructure (*very likely, high confidence*).

Changes to the water cycle have manifold effects beyond those described in this chapter. See the Energy (Ch. 5), Ecosystems (Ch. 8), Agriculture (Ch. 11), Built Environment (Ch. 12), Transportation (Ch. 13), and Human Health (Ch. 15) chapters for more information.

## *Flood Impacts*

Floods have important roles in creating and maintaining aquatic habitat, in regulating the reproductive cycles of fish and other river organisms, and in replenishing soil and nutrients in floodplains. Land-cover changes have limited these positive impacts and even exacerbated some of the negative consequences of floods. Climate change–driven changes in precipitation amount and duration, snowpack/snowmelt, and soil moisture have combined with land-cover change and increasing property values to increase overall economic damages from floods (Figure 4.12).[82]

## Flood Damages Associated with Precipitation Change




**A portion of observed increases in inland flood damages can be attributed to changes in precipitation.**

**Figure 4.12.** Cumulative inland flood damages (in 2021 dollars) across the contiguous US (gray) and estimated portion due to changes in precipitation (green) are shown for 1988–2021. Over this period, heavy precipitation has increased over most of the US due to climate change (see Figure 2.8 for heavy precipitation changes over the 1958–2021 period). Error bars (in green) show the plausible range of cumulative damages in 2021, calculated using a 95% confidence level. Roughly 20%–46% of increases in observed flood damages can be attributed to increasing precipitation (assuming the same historical development patterns over the period 1988–2021). Other important contributors to flood damage include urbanization and land-use change, which can exacerbate runoff, and growth in the number and value of flood-affected buildings and other assets. Adapted from Davenport et al. 2021.[82]

In urban settings, pavements, roofs, and compacted soils do not absorb water as effectively as natural landscapes, amplifying the effects of heavy precipitation and concentrating flooding. In rural settings, lower amounts of impervious land cover allow soils to hold more rainfall. However, intensive agriculture can reduce the infiltration and water-holding capacity of soils and increase runoff, resulting in flooding.[83]

At major watershed scales, flooding along large river and lake systems causes numerous disruptions, including to rail, roadway, and river transportation; agricultural production; commodity deliveries; and industrial production, as seen during the Mississippi River flood of 2011 (KM 24.4).[84]

Increasing flood activity threatens water quality and ecosystems (Figure 4.2). As floodwaters inundate normally dry areas, they transport debris, chemicals, bacteria, and other contaminants (KM 23.1).[85,86] Heavy precipitation events are overwhelming aging combined stormwater–sewer systems, leading to discharges of contaminated water and raw sewage into receiving waters.[87,88] The upward trajectory of urban flooding impacts will likely continue with changing rainfall patterns and intensity.[89] Groundwater-sourced drinking water is becoming contaminated from standing floodwaters over wellheads and percolation into well-fields,[90] and in farmlands high runoff is discharging fertilizer into streams and lakes, causing harmful algal blooms.[91]

## Drought Impacts

Droughts are driven by many factors, including unsupportable societal demands for water.[92] From a climate perspective, below-normal precipitation is a primary driver of drought, but there is growing acknowledgement that higher temperatures can cause drought to develop or become more intense than would be expected from precipitation deficits alone; higher temperatures drive increased atmospheric demand for moisture—a phenomenon known as hot drought.[75,93,94,95] Above-normal temperatures also contribute to snow drought (Box 4.1) and flash drought, which develops quickly over a few weeks.[96,97] Megadroughts are events of extraordinary duration and severity,[98] and many are documented in paleoclimate records.[99,100] Temperature's contribution to drought makes it clear that warming associated with climate change could increase the frequency, severity, and/or duration of drought[73,101,102] and drive aridification, a long-term shift toward a drier climate, which is a concern in already dry parts of the West.[76]

Between 1980 and 2022, drought and related heatwaves in the US caused $334.8 billion (in 2023 dollars as of July 2023) in damages; only tropical cyclones and severe storms were more costly (KM 22.1).[2] Droughts often reduce agricultural productivity and strain water systems,[103,104] driving shortages in water supplies and threatening power generation (KM 5.1).[105] River and lake transportation is also at risk due to drought (KM 24.4).

Drought stresses terrestrial and aquatic ecosystems[106] by leading to increased water temperature and salinity, reduced nutrients, lower oxygen levels, concentrated contaminants (Figure 4.2), loss of surface and groundwater connections, and declining productivity.[107,108] In addition, drought can exacerbate other disturbances such as pests and wildfire.[109] Ecosystems can be resilient under normal climate variability, but recovery after drought in a changed climate may not be possible, leading to the loss of ecosystem services and loss or migration of native and invasive species (Figure 8.6).[110,111]

Groundwater quality is also threatened by heat and drought. Warmer soil and groundwater temperatures can lead to decreased oxygen saturation, lower pH, and enhanced mineral weathering, all of which reduce water quality,[112] and coastal and island aquifers are at risk of seawater intrusion, rendering groundwater unpotable and potentially harming infrastructure (Figure 4.2; KMs 9.2, 21.2, 23.3, 28.2, 30.1).

Drought conditions have historically resulted in increased groundwater pumping in some regions of the US, a practice projected to increase with climate change.[55,56,113] Declining groundwater levels due to pumping can reduce streamflow (Figure 4.13)[48] and result in land subsidence.[114]

### San Pedro River, Arizona

**The San Pedro River in Arizona has been depleted by groundwater pumping, drying up wetlands and wildlife habitat.**

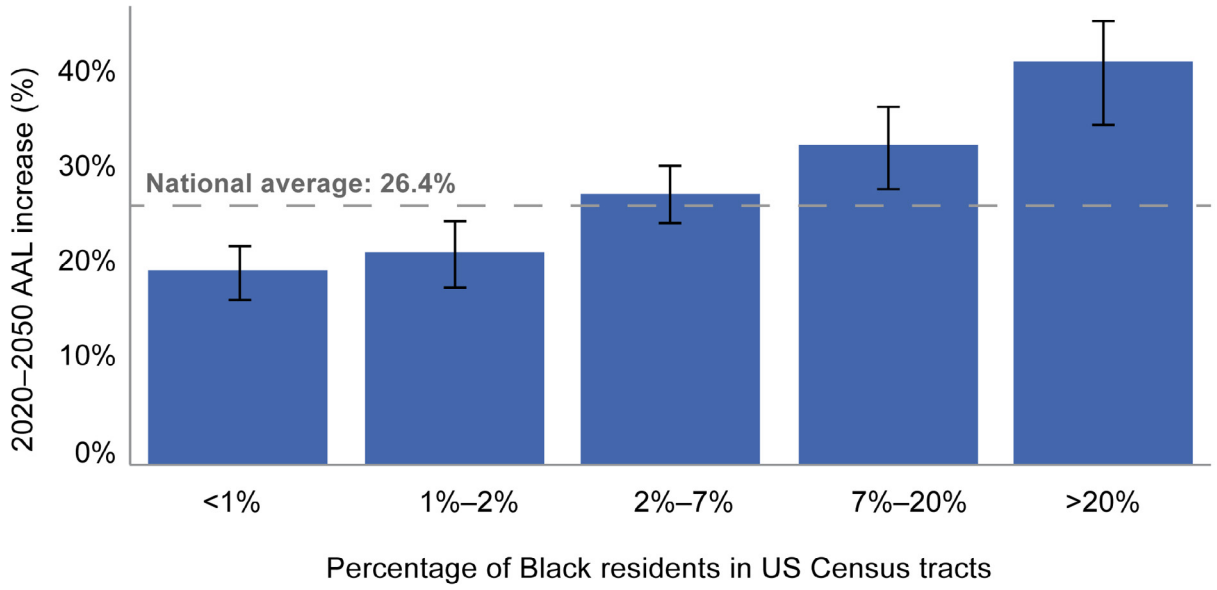
**Figure 4.13.** Groundwater pumping can reduce surface water supplies. One example is the San Pedro River in Arizona, where pumping that began in the 1940s has deprived wetlands and wildlife habitat of fresh water.[115] Photo credit: CochiseVista/iStock via Getty Images.

## *Disproportionate Impacts*

Climate change creates unequal burdens on people and communities.[116,117,118] People who live along coasts and rivers or who work in agriculture and fisheries have increased exposure to water-related hazards.[119,120,121] Older adults, children, and residents of low-income neighborhoods and rural areas are at greatest risk of exposure to pathogens and pollutants from climate change–driven impacts to water quality.[122,123,124]

Many Tribal and Indigenous communities reside in areas subject to coastal and riverine flooding and risk displacement from lands with cultural significance.[125,126,127] Neighborhoods that are home to racial minorities and people with low incomes have the highest inland flood exposures in the South.[128] Hispanic residents are 50% more likely to live in the 500-year floodplain,[129] while Black communities are projected to bear a disproportionate share of future flood damages (Figure 4.14; Box 4.2).[130] Drought can also have unequal impacts depending on economic sector, access to water resources, ability to irrigate, reliance on electricity, and socioeconomic status.[131]

## Projected Increases in Average Annual Losses (AALs) from Floods by 2050




**Losses due to floods are projected to increase disproportionately in US Census tracts with higher percentages of Black residents.**

**Figure 4.14.** Average annual losses—economic damages in a typical year—due to floods in census tracts with a Black population of at least 20% are projected to increase at roughly twice the rate of that in tracts where Black residents make up less than 1% of the population. Black bars represent 95% confidence intervals. Adapted from Wing et al. 2022[130] [CC BY 4.0].

## Box 4.2. Climate Change, Urban Flooding, and Inequality

Hurricane Harvey dropped record-breaking rainfall onto the Houston and Beaumont–Port Arthur metropolitan areas in August 2017 (Figure 4.15). The flooding, exacerbated by extensive urbanization, killed more than 100 people and caused an estimated $147.6 billion in damages (in 2022 dollars).[132] Harvey's rainfall was estimated to be about 15% to 20% heavier than it would have been without human-caused warming,[133,134,135] which increased the flooded area in the Greater Houston area by 14%,[136] leading to 32% more homes being flooded.[137] Many of the flooded properties were located outside FEMA's designated 100-year floodplains and not covered by federal flood insurance. Such properties were disproportionately inhabited by Black and Hispanic residents.[138] People with disabilities and residents of subsidized housing were also disproportionately affected.[139,140] Climate change's impact on flooding is expected to worsen these types of inequalities.

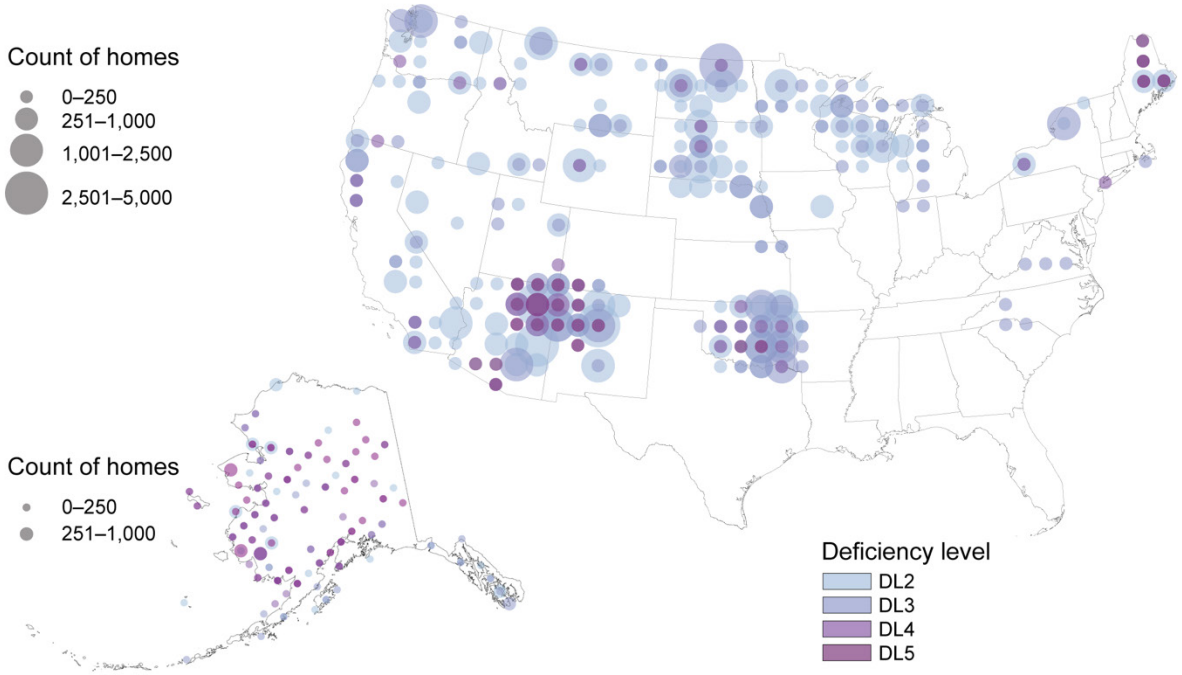
### Residential Flooding from Hurricane Harvey

**Flooding from Hurricane Harvey inundated residential neighborhoods in Port Arthur, Texas.**

**Figure 4.15.** Photo credit: Staff Sgt. Daniel J. Martinez, US Air National Guard.

Across the Nation, drinking water delivery infrastructure is aging and deteriorating (KM 12.2), increasing the risks of contamination and delivery of unpotable water.[141] More than 1,000 community water systems—primarily serving older adults and people who are economically disadvantaged, rural, Indigenous, or with less education[142]—are already providing poor-quality water and are not prepared to cope with climate change-driven flooding, drought, and waterborne diseases (Figure 4.2; KMs 15.1, 15.2). For some Tribal and Indigenous communities, water infrastructure deficiencies threaten their social, physical, and mental well-being and impair their ability to thrive (KM 16.1).[143,144,145] Figure 4.16 shows the distribution and severity of sanitation facility deficiencies in American Indian and Alaska Native homes.[146]

## American Indian and Alaska Native Homes Requiring Water and Sewer System Improvements




**Water infrastructure supporting Tribal and Indigenous Peoples is particularly ill-equipped to handle increases in flooding and drought.**

**Figure 4.16.** The Indian Health Service (IHS) maintains a database of American Indian and Alaska Native (AI/AN) homes requiring sanitation facility improvements within IHS service areas. The figure shows sanitation deficiency levels in AI/AN homes across the country ranging from level 2 (capital improvements are necessary to meet domestic sanitation needs) to level 5 (lacks a safe water supply and a sewage disposal system). The IHS does not collect data for Hawai'i, the US-Affiliated Pacific Islands, or the US Caribbean, but elevated rates of plumbing deficiencies are documented in those regions.[142] Figure credit: Indian Health Service.

## Key Message 4.3

## Progress Toward Adaptation Has Been Uneven

The ability of water managers to adapt to changes has improved with better data, advances in decision-making, and steps toward cooperation. However, infrastructure standards and water allocation institutions have been slow to adapt to a changing climate (*high confidence*), and efforts are confounded by wet and dry cycles driven by natural climate variability (*very likely, high confidence*). Frontline, Tribal, and Indigenous communities are heavily impacted but lack resources to adapt effectively, and they are not fully represented in decision-making (*high confidence*).

### Approaches to Management and Planning

Uncertainty from natural variability has always been part of water resources planning, but as climate change affects different components of the water cycle, uncertainties around extreme events and water availability have increased. Responses to these growing uncertainties include climate adaptation and hazard mitigation through watershed management (KMs 6.1, 6.2);[147] nature-based solutions (KM 8.3); planned relocation;[148,149] floodplain management;[150] water conservation and reuse;[151,152] decision science;[153,154] reservoir optimization and artificial intelligence applications;[155,156,157] improved weather and streamflow forecasts;[158] municipal planning;[159,160,161] adaptive management systems;[162] stakeholder–scientist partnerships;[163] and adaptation guidance (KM 31.4).[164,165,166,167]

### Adaptation Constraints

Climate change is overtaking water resources policymaking,[168,169] making risk reduction a continual exercise in catching up. For example, current rates of precipitation change outpace the regulatory changes needed to cope with them. Key rainfall metrics for design and decision-making are widely outdated;[170,171] updating these metrics is essential to protecting communities. While there have been recent advances in data collection, statistical methods, climate modeling, and weather forecasting, progress is difficult, in part because regulations, codes, and standards involve competing interests and often span multiple jurisdictions.[172,173,174]

### Conflict, Competition, and Collaboration

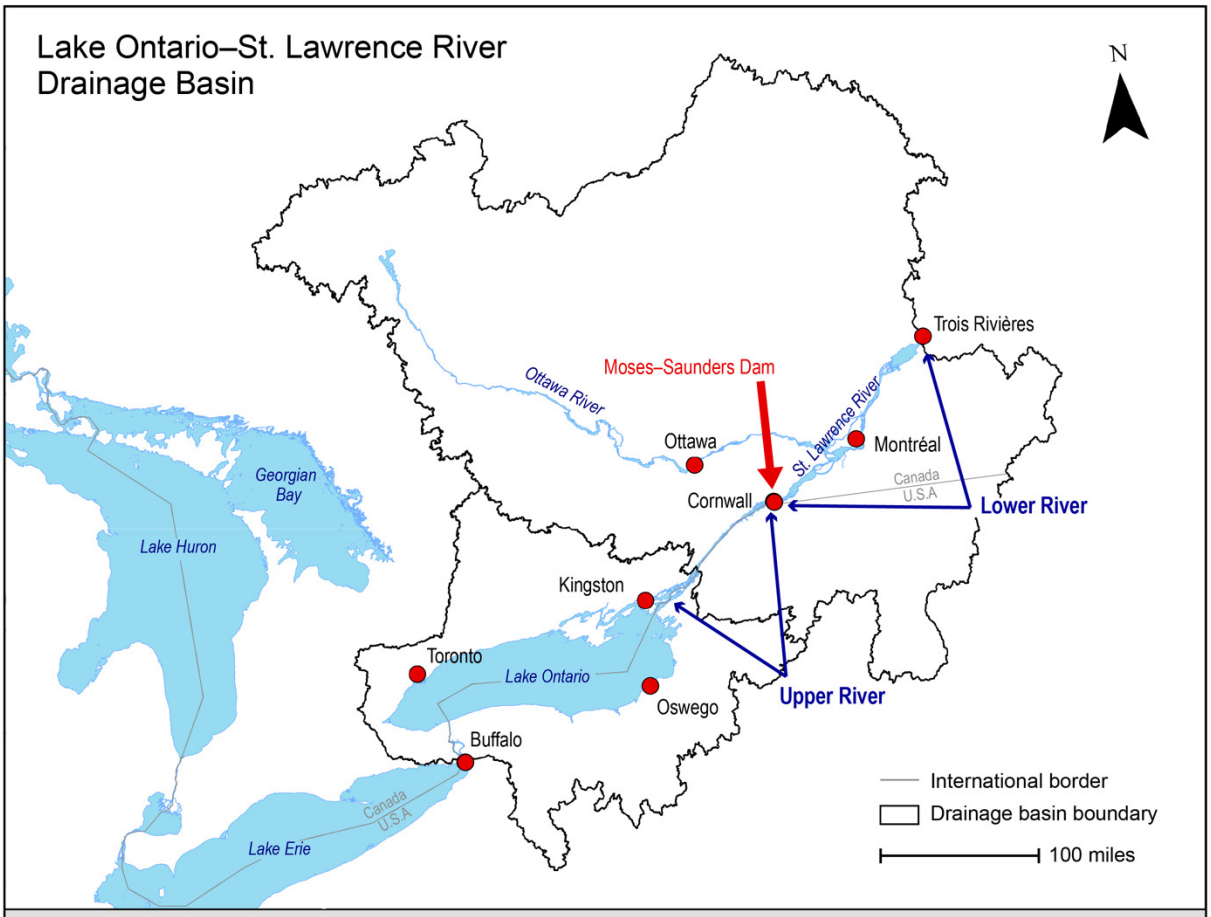
Climate change impacts to water supplies can result in competition, collaboration, or conflict. Frequently, water disputes in the western US are resolved through litigation.[175,176] However, under current severe drought conditions and in the context of existing legal frameworks, water interests in the Colorado River basin, including Mexico, are struggling to avoid litigation through negotiated settlements and voluntary use reduction (Box 28.1).[177,178,179] Some of these efforts now include Tribes and other water users who have traditionally been excluded from participation in negotiations, although representation remains uneven.[180]

In areas where flood risk is increasing, collaboration on flood hazard management at regional scales has become more urgent, as cooperation can provide solutions that are not available at the local scale (Box 4.3). This is especially true in the Midwest, where flooding is often regional and local solutions can push flood risks downstream.[181]

## Box 4.3. International Cooperation in the Great Lakes

The Great Lakes, which contain the largest quantity of surface fresh water on Earth, are shared by two Canadian provinces, eight US states, and many sovereign Tribes and First Nations. Although ripe for conflict and competition, the waters have been equitably shared since the 1909 Boundary Waters Treaty.[182] In 2017, a management plan regulating Lake Ontario's levels and outflows was implemented (Figure 4.17).[183] It was the culmination of more than 16 years of scientific study, public engagement, and governmental review, including a collaboratively built model of the physical, environmental, and economic responses of the system to management and climate alternatives. Performance indicators yielded insights and quantified trade-offs, leading to a plan that balances flooding along the lake's New York and Ontario shorelines against flooding downstream on the St. Lawrence River at Montreal, Quebec. The plan also aims to restore the health and diversity of coastal wetlands and protect against extreme high and low water levels. An adaptive management committee evaluates the plan's performance under climate change and recommends adjustments.

### Resolving Water Conflicts within the Lake Ontario–St. Lawrence River System




Plan 2014 determines outflows to the St. Lawrence River at Cornwall/Massena. Competing regions include Lake Ontario, Upper River, and Lower River. Interests include coastal flooding, erosion, shore protection, commercial navigation, hydropower, recreational boating, municipal and industrial water intakes, and ecological performance.

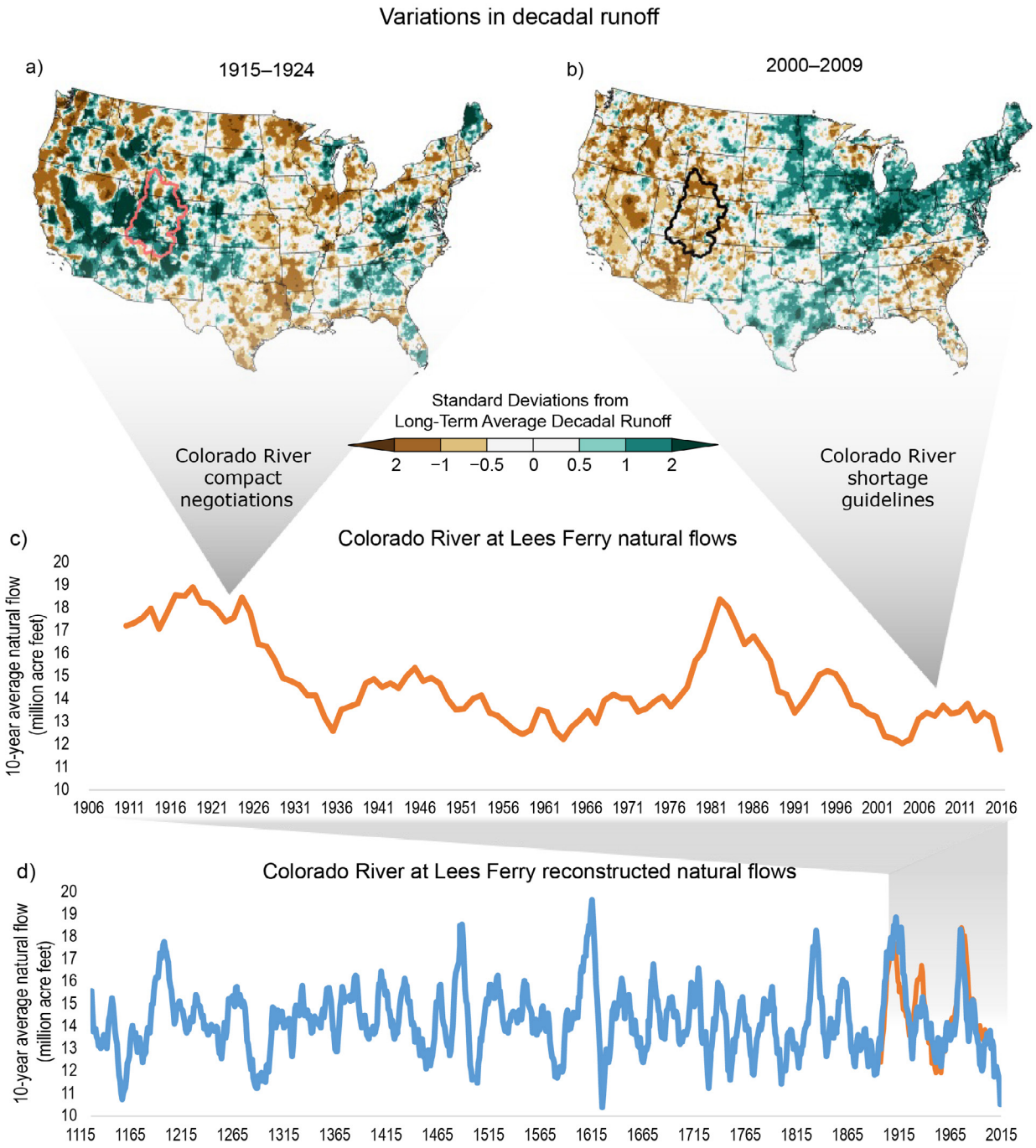
**Plan 2014 was developed to manage Lake Ontario–St Lawrence River water levels, restore ecosystems, and account for climate change.**

**Figure 4.17.** The map shows the geographic setting for an international plan between the US and Canada to cooperatively manage Lake Ontario. The plan balances interests upstream of the Moses-Saunders Dam with downstream interests. The collaborative framework used to develop the plan serves as a model of a successful approach to resolving water conflicts. Adapted from International Joint Commission 2014.[183]

## *The Effect of Natural Variability on Policy*

Historical records and paleoecological evidence, such as tree ring data, show that natural variability in the climate system has resulted in multidecadal wet and dry spells in the past. [99] Climate projections indicate this pattern will continue, challenging planning and policy formulation for adaptation to climate change, and suggesting that durable and realistic long-term perspectives are necessary for robust policy development. For example, natural variability brought the wettest period in the past 1,200 years to the Colorado River in the early 20th century (Figure 4.18). The Colorado River Compact, negotiated in that period of relative abundance, allocated far more water than the river has since provided.[184] In the last years of the 20th century, sustained high reservoir levels prompted the development of guidelines for surplus allocation, but by the time those guidelines had been finalized, the current 22year drought had begun.[73] That drought has triggered unprecedented water use restrictions and is leading to more realistic policy discussions (Box 28.1).[177] Similar variability is present in climate and hydrology projections through the end of this century. The amplitude of projected 30-year-average wet and dry spells on the Colorado River may be twice the average projected decrease in streamflow by the end of this century;[185] as a result, multidecadal natural variability almost certainly will again lead to prolonged wet periods,[186] though diminished by higher temperatures.

## Natural Hydrologic Variability Influences Policy




**Natural hydrologic variability can promote urgency or complacency in long-term planning.**

**Figure 4.18.** The figure shows hydrologic variability in both space and time: (**a**, **b**) runoff variability (a surrogate for streamflow variability) across the country between two decades, with the boundary of the Upper Colorado River Basin shown; and streamflow variability across time with (**c**) estimates of Colorado River flows from historical observations and (**d**) reconstructed flows from ancient tree rings (blue line), with data from (c) shown in orange. Wedges point to two negotiated policy events. Figure credit: Lynker and University of Colorado Boulder.

## Adaptation Challenges Faced by Tribal and Indigenous Communities

To address water-related climate impacts, Tribes have voiced the need for climate impact assessments as a first step to resilience planning and identified information about climate change impacts to water as a top priority.[187] Many Indigenous communities lack data on water quality despite disproportionately experiencing water quality deficiencies.[188] Other data types critical to Tribal water management decisions are streamflow, temperature, precipitation, snowpack, and soil moisture, but these are not always available through federal information sources.[187]

Food security, protection of Traditional Knowledge, and Tribal capacity to implement adaptation plans, monitor and collect data, and conduct climate vulnerability assessments are also high priorities. Federally Recognized Tribes are eligible for federal assistance with climate change adaptation, but they face hurdles accessing these limited resources, including agency requirements (e.g., funding matches), lack of Tribal capacity, and navigating interagency processes.

## Progress and Gaps in the Quality and Usability of Information

Water resources planning continues to be informed by past hydrologic records that do not reflect the impacts of climate change. Although some federal, state, and larger local agencies do use climate projections in planning, projections of precipitation, streamflow, water use,[189] and extreme events at the scale of local watersheds are rarely available, particularly outside of the contiguous US. Using projections is also costly because tools and techniques are specialized and not standardized. Finally, climate models project a wide range of uncertainty (Figure 4.3), requiring planners to use their best judgment about how to apply the information.

Data are foundational to adaptation. State and federal agencies have been collecting valuable climate, hydrology, and water use data for over a century, but these data are sparse in lightly populated and lower-income areas.[185] Increasingly, modeling and remote-sensing data are filling the gaps. High-resolution elevation and environmental data collected from airborne and spaceborne platforms provide detailed topographical and hydrological information that can be used to map flood hazards and snowpack[190,191] and refine real-time snow simulation.[192,193] Evapotranspiration is being estimated using satellite remote sensing combined with vegetation models,[194] providing early warning of emerging droughts,[195] and satellites are now being used to detect groundwater depletion.[196] Nevertheless, expanding direct observational data collection is still key to tracking environmental conditions and supporting development and testing of remotely sensed data and models.

# Traceable Accounts

## *Process Description*

With support from the chapter point of contact and the federal coordinating lead author, the chapter lead author selected authors for their expertise in assessing climate impacts to the Nation's surface and groundwater resources and the consequences of those impacts to human and natural systems, with an emphasis on the authors' ability to bring diverse perspectives to the team. The team comprises experts drawn from several regions across the country who work under various employment types (i.e., private business, academic institutions, and local, state, and federal governments), come from diverse backgrounds, and represent a range of combinations of age and gender. The team met virtually multiple times to scope the chapter, with each author offering their own priorities about what a chapter about the Nation's water resources should cover, taking into consideration the goals of this Assessment, the topics covered in previous National Climate Assessments (NCAs), and the topics of the other 31 chapters in the NCA5. The team's discussions revolved around these questions: How are changes in climate influencing water input volume and movement? How are extremes and the notion of extremes changing? How are changes in climate stressing both natural and human-made systems? What are the environmental justice considerations and the distribution of impacts? Are current climate data and tools adequate for decision-makers? And what are the interconnected climate risks? With these questions in mind, the team iteratively developed a draft outline for the chapter. That outline was made available online for public review and comment. The team presented and participated in a virtual, public, four-hour workshop and discussion, collecting comments and suggestions for the chapter from workshop participants. Workshop comments and formally submitted comments were taken into consideration in development of the chapter text. The Third Order Draft was presented to the public by five of the authors in a webinar hosted by Western Water Assessment at the University of Colorado. The author team met virtually at least twice per month during periods when the draft was not out for review. The team also met in person at the NCA5 All-Author Meeting held in April 2023 in Washington, DC. The meetings were used to set interim deadlines, assess the status of tasks, discuss language choices, find consensus on Key Messages and figures, develop responses to comments on drafts, and support each other with references and text reviews.

## Key Message 4.1

## Climate Change Will Continue to Cause Profound Changes in the Water Cycle

### Description of Evidence Base

The hydrologic component maps shown in Figures 4.3, 4.5, 4.6, 4.7, and 4.9 constitute part of the evidence base. They show mid-21st-century projections of water cycle components based on an intermediate scenario (RCP4.5). Projections of water cycle components are available for both RCP4.5 and RCP8.5 scenarios, but both scenarios show similar hydrologic responses at midcentury, neither are available as 100-year projections, and space in this chapter is limited; as a result, only RCP4.5 projections are presented here. The central map of the contiguous US (CONUS) in each of these figures represents the average of all 32 Coupled Model Intercomparison Project Phase 5 (CMIP5) projections chosen for this discussion.[197] The Alaska and Hawai'i maps represent the average of 10 CMIP5 projections. The wettest and driest 20% of projections show the range of outcomes from the 32-projection set for CONUS, illustrating the uncertainty surrounding water cycle responses to climate change. Outside CONUS, downscaled climate projections are limited, especially those needed to map projected changes in hydrologic components for the US Caribbean and US-Affiliated Pacific Islands. The absence of projections for actual evapotranspiration, soil moisture, and

runoff contribute to uncertainty when assessing future water security challenges for these regions. Further information about the data used to generate the maps can be found in the figure metadata.

Because the focus of this chapter is terrestrial fresh water, the authors relied heavily on Chapter 2 (Climate Trends) and Chapter 3 (Earth System Processes) for their assessments of precipitation trends and projections, particularly extreme precipitation trends and projections.

Regarding evapotranspiration, there is general consensus that warming temperatures will enhance evaporative demand (potential evapotranspiration, PET) across the Nation (Ch. 3);[43,44,75] however, uncertainties in vegetation response to warming reduce confidence in evapotranspiration (ET) projections.[75] In many parts of the country, projected changes in annual evapotranspiration by the end of this century are not robust, and there is disagreement among models across the southern states and parts of the central US.[43] The degree and sometimes direction of observed changes in PET and ET are also less certain, particularly east of the Rocky Mountains, due to differences in the trends of the variables that force PET.[12] Nor are these trends well supported by direct observation. There is a lack of information on more recent trends in pan evaporation across the US. Pan evaporation is a useful concept to estimate atmospheric evaporative demand but it is strongly affected by local environmental conditions, which can drive contradictory trends in pan evaporation across a broader region,[198] as is observed across the US.[199] For example, increases in local humidity (e.g., from irrigation) or land-use changes (e.g., changes in tree density near the pans) could affect evaporation from the pans. Therefore, pan evaporation may not provide a reliable indication of regional-scale trends in evaporative demand. The disagreement among observational data and reanalyses limits our confidence in past ET and PET trends. Complexities related to vegetation, as well as the competing effects of multiple evaporation drivers, make assigning nationally consistent likelihood and confidence challenging. However, the balance of evidence suggests with *medium confidence* that evaporation is expected to increase in places where moisture is not a limiting factor to atmospheric demand.

There is widespread consensus that increases in temperature will decrease the proportion of US precipitation that falls as snow,[14,15,24,43] decrease snow extents,[24,25] advance the timing of snowmelt rates and pulses,[16,27] increase the prevalence of rain-on-snow events,[70,71] and influence how snow water resources are partitioned to runoff.[19,20]

Since parts of Alaska and the highest elevations in the contiguous US may be cold enough to sustain snowfall in future climates, some studies have projected increases in snow volume in these locations with future increases in precipitation. However, those increases in snow are expected to be vastly outweighed by the future decreases in snow elsewhere, particularly across the western US and by the late 21st century for all intermediate (RCP4.5 and SSP2-4.5) and higher scenarios.

It is well established that groundwater and surface water are connected resources and that groundwater can help stabilize surface water supplies.[47,48] Similarly, there is agreement that loss of shallow groundwater can exacerbate droughts and decrease streamflow. There is also agreement that warmer temperatures will increase water demand and that this could increase groundwater pumping.[52,53,54]

## Major Uncertainties and Research Gaps

Uncertainties stem from future projections of climate. This may be particularly true for late-21st-century projections that are dependent on the degree to which societies will respond to climate change. The literature employs different projections and emissions scenarios, as well as metrics and measurements that vary in their degree of climate sensitivity, resulting in studies that are not always directly comparable.

Understanding recent and potential future flood responses to climate change is difficult for several reasons. Floods are the product of complex subseasonal to interannual interactions between rainfall, soil moisture, evapotranspiration, snowpack/melt, and other processes. Isolating climate change impacts on

inland flooding is further complicated by the hydrologic "replumbing" wrought by urbanization and dams. For these reasons, the translation of rainfall trends into flood changes is complex and poorly understood. National[65,200] and global[201] examination of historical flood records has concluded that climate influences have been relatively limited, contradicting an earlier study that argued that the largest floods have increased in severity.[202] This latter argument is further contradicted by evidence that floods in the central US have become more common but not more intense.[203,204]

However, major floods are by definition rare, making detection and attribution of changes difficult. Thus, a lack of statistically significant trends in observed floods does not necessarily indicate that such events are not changing. Indeed, a relatively limited number of geographically focused case studies have painted complex pictures of climate-related flood changes that are lacking in broader regional and national analyses. Additional place-based case studies—as opposed to regional- or national-scale analyses—could help unravel the complex interactions between climate and non-climate flood drivers.

Given the first-order influence of temperature and precipitation change on snowfall, there is high certainty that future US snow cover, snow volume, and snow persistence will change.[24] However, there is some disagreement in the literature about the extent and direction (positive or negative) of change in surface water availability with future changes in climate. Existing studies indicate both increases and decreases in future runoff for different US hydroclimatic regimes.

In particular, there is uncertainty in the degree to which temperature may impact flow in some major river systems in the West.[205,206] Significant disagreements in the direction of observed soil moisture trends remain,[38,39,40] largely because it can be challenging to estimate with remote sensing or models, and the existing in situ soil moisture–monitoring network is insufficient.[37] Uncertainties can also be introduced because not all products are directly comparable, capturing trends over slightly different depths, although modest differences are probably not a major source of error. There is also uncertainty in soil moisture projections related to model, season, and soil depth.[38,42,43]

Similarly, there is uncertainty in both the magnitude and direction of groundwater storage changes, primarily due to uncertainty in future groundwater management policy and uncertainty in future recharge. This is due to uncertainty in both the human response to changing climate conditions and research gaps in quantifying natural groundwater recharge. Groundwater pumping is controlled by a myriad of human factors such as population, water policy, crop choices, and irrigation technology. While it is well established that warmer temperatures can increase water demand,[52,53,54] and historical trends demonstrate unsustainable groundwater usage in the past (as discussed in NCA4), future groundwater pumping increases will depend on water management practices and policy. Groundwater recharge is similarly uncertain.[50,51] Projected increases in large precipitation and flooding events are expected to increase recharge (known as episodic recharge events). However, the quantity of this recharge is less certain and highly dependent on the nature and timing of the storms that occur. Also, while increases in recharge may be counteracted by changes in plant water usage and snowpack that can decrease natural recharge, the magnitude of these recharge changes has not been well quantified. Separating the impacts of groundwater pumping from climate trends is particularly challenging due to a lack of long-term groundwater monitoring wells, especially outside of the most heavily groundwater-developed areas.

## Description of Confidence and Likelihood

The author team determined that the evidence points to *medium confidence* that there will continue to be increases in precipitation in Alaska and in the northern and eastern regions of the US and decreases in precipitation in the Caribbean and the Southwest. Despite lingering uncertainties around average precipitation, there is *very high confidence* from both observations and projections that extreme precipitation events are becoming more frequent nationwide, and that it is *very likely* this trend will continue in the

future. The disagreement among observational data and reanalyses limits our confidence in past ET and PET trends. Complexities related to vegetation, as well as the competing effects of multiple evaporation drivers, make assigning nationally consistent likelihood and confidence challenging. However, the balance of evidence suggests with *medium confidence* that evaporation will increase in places where moisture is not a limiting factor to atmospheric demand. Based on current trends and climate model projections, there is *high confidence* and it is *very likely* that warming temperatures will increase the demand for surface and groundwater for crops and human use. Given the direct influence of rising temperatures on snow, there is *high confidence* and it is *very likely* that the extent, volume, and duration of snow cover and melt upon which human and natural systems rely is and will continue to be reduced by warming.

## Key Message 4.2

## Water Cycle Changes Will Affect All Communities, with Disproportionate Impacts for Some

### Description of Evidence Base

Observational records now span time periods long enough to evaluate changes in the volume, variability, and timing of water availability.[11] The magnitude of these changes, and their agreement with model projections, vary with hydroclimate regimes across the US.

While it has been difficult to establish clear linkages between increases in extreme precipitation and trends in "traditional" measures of flood activity such as peak streamflow rate, attribution studies have apportioned some of the historical increases in flood damage to precipitation change.[68,69] It is probable that many of these increases have been concentrated in urbanized watersheds, which are more sensitive to rainfall than rural and natural settings.[74] Flood vulnerability, including in urbanized areas, tends to be concentrated in historically marginalized and socioeconomically disadvantaged neighborhoods.[130] There is increasing consensus that systematically disadvantaged communities have been and will continue to be most impacted by these hazards, due to factors such as inadequate climate/hydrological monitoring, deferred infrastructure maintenance, and insufficient access to recovery resources.[207]

There is ample literature describing the impacts of floods, fires, and drought events on a wide variety of water quality hazards.[6] These studies provide insights into impacts to water quality hazards from intensified events due to climate change, and studies specific to climate change impacts on water quality are becoming more prevalent. There are some reports of specific benefits to contaminant concentrations from increased or decreased precipitation, but there is no consensus that water quality will improve with climate change.

There is widespread consensus that increases in air temperature will impact water quality by increasing water temperatures, resulting in less oxygen-rich water, exacerbating harmful algal blooms, increasing pathogens, and creating problems with drinking water taste and odor.[6,7]

Similarly, there is consensus that increased precipitation and intensity will degrade water quality due to urban storm water and combined sewer overflows, increased agricultural runoff, and riverine flooding. There is less certainty in regions of the country where precipitation is not increasing or decreasing. Compounding factors of increasing temperatures and aging stormwater and sewer systems and water reservoirs can exacerbate problems due to too much or too little water.

The literature is rife with observations of segments of the population being negatively affected by climate change, especially water-related hazards. There is consensus that these negative impacts of water-related climate change will be felt disproportionately among marginalized and low-income people.[122]

### Major Uncertainties and Research Gaps

There is moderate uncertainty about the degree to which land-surface changes will drive nonstationary changes to the volume and timing of water resources. There is a lack of research on the linkages between climate change and flooding.[68] There is uncertainty about the extent to which traditional design storms—that is, storms of particular intensity and duration, used in floodplain and built environment planning—and flooding assumptions based on older observations reflect current and future flood conditions.[171] Additional research into the effects of climate change on water quality would improve our understanding of impacts, particularly in the face of compounding factors such as aging infrastructure, wildfires, and increased agricultural runoff.

### Description of Confidence and Likelihood

There is strong evidence that climate change imparts a number of important shifts in local and regional hydrologic cycles, and that when combined with land-use changes and other human factors, increases are *likely* in the frequency, severity, duration, and damages from floods (*high confidence*) and drought impacts are increasing (*medium confidence*). There is a more limited body of work on the effects of climate change on water quality; thus there is *medium confidence* that climate change is degrading water quality. However, there is still uncertainty about how climate drivers may shape harmful algal blooms, a significant factor in water quality. Based on the vast literature documenting current, disparate impacts to frontline communities from floods, droughts, and the exposures they bring, there is *high confidence* and it is *very likely* that frontline communities will be at disproportionate risk from water-related hazards exacerbated by climate change.

## Key Message 4.3

## Progress Toward Adaptation Has Been Uneven

### Description of Evidence Base

There are many examples of climate change overtaking the speed of adaptation,[168,169] including communities caught off guard by extreme precipitation and drought events amplified by climate change.[96,133] A wide array of literature over the past decade has identified the safety and economic risks posed by aging water systems and changing hydrology.[87] Since the publication of NCA4, expanded data collection, improved climate projections, and better short- to midterm forecasts support better water resource management and planning. However, local water resource managers are still struggling to find accessible, usable science and data at the appropriate spatial scale, and they continue to rely on historical records that often do not reflect current and future water availability and timing. Disaster management literature contains many examples of public complacency and/or urgency in preparing for extreme events.[208]

A growing literature focuses on providing scientific information that is more usable for water resource planning and management.[164] There has been less work in assessing success and evaluating how equitable these approaches have been.[209]

A number of retrospective reviews highlight the omission of frontline, Tribal, and Indigenous voices and benefits from water projects.[180] Long-standing legal entitlements, established before climate change was a consideration, are well documented. The bulk of senior water rights and legal entitlements in the West are held by Tribes and agricultural water users but governed by state and federal decrees, agreements, and compacts that were not written to be flexible or responsive to a changing climate. Current literature is documenting these barriers and assessing emerging approaches to work past them.[177]

## Major Uncertainties and Research Gaps

Building climate resilience in hydrologic systems is challenging given the high uncertainty of climate variability and change. Gaps in actionable local-scale water data are particularly problematic, especially translating projections from global climate models to the regional and local level. System-level approaches and the use of resilience metrics are also areas ripe for improvement.

There is moderate uncertainty about the degree to which changes to land surface characteristics will drive changes to the volume and timing of water resources, and the degree to which existing infrastructure and historically defined allocations will be able to adapt. A large part of this uncertainty is related to how quickly human actions and policies react to hydrologic hazards.

## Description of Confidence and Likelihood

Rising water-related disaster costs, communities ill-prepared for floods and droughts, and basin water users deferring difficult water allocation decisions are just a few of the pieces of evidence leading to *high confidence* that adaptation efforts are proceeding unevenly relative to the rate of climate change and that this is *very likely* (with *high confidence*) due in part to natural climate variability masking long-term changes. The history of water resources decision-making rarely includes participation by frontline, Tribal, or Indigenous individuals or communities. Their exclusion from negotiations, compacts, decrees, and other allocation actions supports an assessment of *high confidence* that frontline, Tribal, and Indigenous communities have not had full representation in water resources decision-making in the past, despite being affected by those decisions.

# References


1. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

2. NCEI, 2023: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

3. Lall, U., T. Johnson, P. Colohan, A. Aghakouchak, C. Brown, G. McCabe, R. Pulwarty, and A. Sankarasubramanian, 2018: Ch. 3. Water. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 145–173. https://doi.org/10.7930/nca4.2018.ch3

4. Delpla, I., A.-V. Jung, E. Baures, M. Clement, and O. Thomas, 2009: Impacts of climate change on surface water quality in relation to drinking water production. *Environment International*, **35** (8), 1225–1233. https://doi.org/10.1016/j.envint.2009.07.001

5. NCEH, 2022: Climate Effects on Health. Centers for Disease Control and Prevention, National Center for Environmental Health, accessed May 3, 2022. https://www.cdc.gov/climateandhealth/effects/default.htm

6. Nijhawan, A. and G. Howard, 2022: Associations between climate variables and water quality in low- and middle-income countries: A scoping review. *Water Research*, **210**, 117996. https://doi.org/10.1016/j.watres.2021.117996

7. Shukla, N., S. Gupta, and S. Rai, 2023: Ch. 7. Potential impacts of climatic changes and human activity on water quality. In: *Environmental Processes and Management: Tools and Practices for Groundwater*. Shukla, P., P. Singh, and R.M. Singh, Eds. Springer, Cham, Switzerland, 103–111. https://doi.org/10.1007/978-3-031-20208-7_7

8. Chow, A.T., K.-P. Tsai, T.S. Fegel, D.N. Pierson, and C.C. Rhoades, 2019: Lasting effects of wildfire on disinfection by-product formation in forest catchments. *Journal of Environmental Quality*, **48** (6), 1826–1834. https://doi.org/10.2134/jeq2019.04.0172

9. Robinne, F.-N., D.W. Hallema, K.D. Bladon, M.D. Flannigan, G. Boisramé, C.M. Bréthaut, S.H. Doerr, G. Di Baldassarre, L.A. Gallagher, A.K. Hohner, S.J. Khan, A.M. Kinoshita, R. Mordecai, J.P. Nunes, P. Nyman, C. Santín, G. Sheridan, C.R. Stoof, M.P. Thompson, J.M. Waddington, and Y. Wei, 2021: Scientists' warning on extreme wildfire risks to water supply. *Hydrological Processes*, **35** (5), e14086. https://doi.org/10.1002/hyp.14086

10. Corson-Dosch, H.R., C.S. Nell, R.E. Volentine, A.A. Archer, E. Bechtel, J.L. Bruce, N. Felts, T.A. Gross, D. Lopez-Trujillo, C.E. Riggs, and E.K. Read, 2023: The Water Cycle. USGS General Information Product 221, 1 sheet. U.S. Geological Survey, Reston, VA. https://doi.org/10.3133/gip221

11. Jasinski, M.F., J.S. Borak, S.V. Kumar, D.M. Mocko, C.D. Peters-Lidard, M. Rodell, H. Rui, H.K. Beaudoing, B.E. Vollmer, K.R. Arsenault, B. Li, J.D. Bolten, and N. Tangdamrongsub, 2019: NCA-LDAs: Overview and analysis of hydrologic trends for the National Climate Assessment. *Journal of Hydrometeorology*, **20** (8), 1595–1617. https://doi.org/10.1175/jhm-d-17-0234.1

12. Albano, C.M., J.T. Abatzoglou, D.J. McEvoy, J.L. Huntington, C.G. Morton, M.D. Dettinger, and T.J. Ott, 2022: A Multidataset assessment of climatic drivers and uncertainties of recent trends in evaporative demand across the continental United States. *Journal of Hydrometeorology*, **23** (4), 505–519. https://doi.org/10.1175/jhm-d-21-0163.1

13. Tercek, M.T., D. Thoma, J.E. Gross, K. Sherrill, S. Kagone, and G. Senay, 2021: Historical changes in plant water use and need in the continental United States. *PLoS ONE*, **16** (9), e0256586. https://doi.org/10.1371/journal.pone.0256586

14. Hale, K.E., A.N. Wlostowski, A.M. Badger, K.N. Musselman, B. Livneh, and N.P. Molotch, 2022: Modeling streamflow sensitivity to climate warming and surface water inputs in a montane catchment. *Journal of Hydrology: Regional Studies*, **39**, 100976. https://doi.org/10.1016/j.ejrh.2021.100976

15. Harpold, A.A., M.L. Kaplan, P.Z. Klos, T. Link, J.P. McNamara, S. Rajagopal, R. Schumer, and C.M. Steele, 2017: Rain or snow: Hydrologic processes, observations, prediction, and research needs. *Hydrology and Earth System Sciences*, **21** (1), 1–22. https://doi.org/10.5194/hess-21-1-2017

16. Musselman, K.N., N. Addor, J.A. Vano, and N.P. Molotch, 2021: Winter melt trends portend widespread declines in snow water resources. *Nature Climate Change*, **11** (5), 418–424. https://doi.org/10.1038/s41558-021-01014-9

17. Barnhart, T.B., N.P. Molotch, B. Livneh, A.A. Harpold, J.F. Knowles, and D. Schneider, 2016: Snowmelt rate dictates streamflow. *Geophysical Research Letters*, **43** (15), 8006–8016. https://doi.org/10.1002/2016gl069690

18. Evan, A. and I. Eisenman, 2021: A mechanism for regional variations in snowpack melt under rising temperature. *Nature Climate Change*, **11** (4), 326–330. https://doi.org/10.1038/s41558-021-00996-w

19. Harpold, A.A. and P.D. Brooks, 2018: Humidity determines snowpack ablation under a warming climate. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (6), 1215–1220. https://doi.org/10.1073/pnas.1716789115

20. Musselman, K.N., M.P. Clark, C. Liu, K. Ikeda, and R. Rasmussen, 2017: Slower snowmelt in a warmer world. *Nature Climate Change*, **7** (3), 214–219. https://doi.org/10.1038/nclimate3225

21. Breckheimer, I.K., E.J. Theobald, N.C. Cristea, A.K. Wilson, J.D. Lundquist, R.M. Rochefort, and J. HilleRisLambers, 2020: Crowd-sourced data reveal social–ecological mismatches in phenology driven by climate. *Frontiers in Ecology and the Environment*, **18** (2), 76–82. https://doi.org/10.1002/fee.2142

22. Gergel, D.R., B. Nijssen, J.T. Abatzoglou, D.P. Lettenmaier, and M.R. Stumbaugh, 2017: Effects of climate change on snowpack and fire potential in the western USA. *Climatic Change*, **141** (2), 287–299. https://doi.org/10.1007/s10584-017-1899-y

23. Nolin, A.W. and C. Daly, 2006: Mapping "at risk" snow in the Pacific Northwest. *Journal of Hydrometeorology*, **7** (5), 1164–1171. https://doi.org/10.1175/jhm543.1

24. Siirila-Woodburn, E.R., A.M. Rhoades, B.J. Hatchett, L.S. Huning, J. Szinai, C. Tague, P.S. Nico, D.R. Feldman, A.D. Jones, W.D. Collins, and L. Kaatz, 2021: A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment*, **2** (11), 800–819. https://doi.org/10.1038/s43017-021-00219-y

25. Vano, J.A., B. Nijssen, and D.P. Lettenmaier, 2015: Seasonal hydrologic responses to climate change in the Pacific Northwest. *Water Resources Research*, **51** (4), 1959–1976. https://doi.org/10.1002/2014wr015909

26. Rauscher, S.A., J.S. Pal, N.S. Diffenbaugh, and M.M. Benedetti, 2008: Future changes in snowmelt-driven runoff timing over the western US. *Geophysical Research Letters*, **35** (16). https://doi.org/10.1029/2008gl034424

27. Li, D., M.L. Wrzesien, M. Durand, J. Adam, and D.P. Lettenmaier, 2017: How much runoff originates as snow in the western United States, and how will that change in the future? *Geophysical Research Letters*, **44** (12), 6163–6172. https://doi.org/10.1002/2017gl073551

28. Qin, Y., J.T. Abatzoglou, S. Siebert, L.S. Huning, A. AghaKouchak, J.S. Mankin, C. Hong, D. Tong, S.J. Davis, and N.D. Mueller, 2020: Agricultural risks from changing snowmelt. *Nature Climate Change*, **10** (5), 459–465. https://doi.org/10.1038/s41558-020-0746-8

29. Sturm, M., M.A. Goldstein, and C. Parr, 2017: Water and life from snow: A trillion dollar science question. *Water Resources Research*, **53** (5), 3534–3544. https://doi.org/10.1002/2017wr020840

30. Fountain, A.G., C. Gray, B. Glenn, B. Menounos, J. Pflug, and J.L. Riedel, 2022: Glaciers of the Olympic Mountains, Washington—The past and future 100 years. *Journal of Geophysical Research: Earth Surface*, **127** (4), e2022JF006670. https://doi.org/10.1029/2022jf006670

31. Hugonnet, R., R. McNabb, E. Berthier, B. Menounos, C. Nuth, L. Girod, D. Farinotti, M. Huss, I. Dussaillant, F. Brun, and A. Kääb, 2021: Accelerated global glacier mass loss in the early twenty-first century. *Nature*, **592** (7856), 726–731. https://doi.org/10.1038/s41586-021-03436-z

32. Menounos, B., R. Hugonnet, D. Shean, A. Gardner, I. Howat, E. Berthier, B. Pelto, C. Tennant, J. Shea, M.-J. Noh, F. Brun, and A. Dehecq, 2019: Heterogeneous changes in western North American glaciers linked to decadal variability in zonal wind strength. *Geophysical Research Letters*, **46** (1), 200–209. https://doi.org/10.1029/2018gl080942

33. Mizukami, N., A.J. Newman, J.S. Littell, T.W. Giambelluca, A.W. Wood, E.D. Gutmann, J.J. Hamman, D.R. Gergel, B. Nijssen, M.P. Clark, and J.R. Arnold, 2022: New projections of 21st century climate and hydrology for Alaska and Hawaiin. *Climate Services*, **27**, 100312. https://doi.org/10.1016/j.cliser.2022.100312

34. Frans, C., E. Istanbulluoglu, D.P. Lettenmaier, A.G. Fountain, and J. Riedel, 2018: Glacier recession and the response of summer streamflow in the Pacific Northwest United States, 1960–2099. *Water Resources Research*, **54** (9), 6202–6225. https://doi.org/10.1029/2017wr021764

35. Yang, L., G. Sun, L. Zhi, and J. Zhao, 2018: Negative soil moisture-precipitation feedback in dry and wet regions. *Scientific Reports*, **8** (1), 4026. https://doi.org/10.1038/s41598-018-22394-7

36. Zhou, S., A.P. Williams, B.R. Lintner, A.M. Berg, Y. Zhang, T.F. Keenan, B.I. Cook, S. Hagemann, S.I. Seneviratne, and P. Gentine, 2021: Soil moisture–atmosphere feedbacks mitigate declining water availability in drylands. *Nature Climate Change*, **11** (1), 38–44. https://doi.org/10.1038/s41558-020-00945-z

37. Ford, T.W. and S.M. Quiring, 2019: Comparison of contemporary in situ, model, and satellite remote sensing soil moisture with a focus on drought monitoring. *Water Resources Research*, **55** (2), 1565–1582. https://doi.org/10.1029/2018wr024039

38. Cheng, S., J. Huang, F. Ji, and L. Lin, 2017: Uncertainties of soil moisture in historical simulations and future projections. *Journal of Geophysical Research: Atmospheres*, **122** (4), 2239–2253. https://doi.org/10.1002/2016jd025871

39. Deng, Y., S. Wang, X. Bai, G. Luo, L. Wu, Y. Cao, H. Li, C. Li, Y. Yang, Z. Hu, and S. Tian, 2020: Variation trend of global soil moisture and its cause analysis. *Ecological Indicators*, **110**, 105939. https://doi.org/10.1016/j.ecolind.2019.105939

40. Gu, X., J. Li, Y.D. Chen, D. Kong, and J. Liu, 2019: Consistency and discrepancy of global surface soil moisture changes from multiple model-based data sets against satellite observations. *Journal of Geophysical Research: Atmospheres*, **124** (3), 1474–1495. https://doi.org/10.1029/2018jd029304

41. Su, L., Q. Cao, M. Xiao, D.M. Mocko, M. Barlage, D. Li, C.D. Peters-Lidard, and D.P. Lettenmaier, 2021: Drought variability over the conterminous United States for the past century. *Journal of Hydrometeorology*, **22** (5), 1153–1168. https://doi.org/10.1175/jhm-d-20-0158.1

42. Berg, A., J. Sheffield, and P.C.D. Milly, 2017: Divergent surface and total soil moisture projections under global warming. *Geophysical Research Letters*, **44** (1), 236–244. https://doi.org/10.1002/2016gl071921

43. Marvel, K., B.I. Cook, C. Bonfils, J.E. Smerdon, A.P. Williams, and H. Liu, 2021: Projected changes to hydroclimate seasonality in the continental United States. *Earth's Future*, **9** (9), e2021EF002019. https://doi.org/10.1029/2021ef002019

44. Condon, L.E., A.L. Atchley, and R.M. Maxwell, 2020: Evapotranspiration depletes groundwater under warming over the contiguous United States. *Nature Communications*, **11** (1), 873. https://doi.org/10.1038/s41467-020-14688-0

45. Maxwell, R.M. and S.J. Kollet, 2008: Interdependence of groundwater dynamics and land-energy feedbacks under climate change. *Nature Geoscience*, **1** (10), 665–669. https://doi.org/10.1038/ngeo315

46. Russo, T.A. and U. Lall, 2017: Depletion and response of deep groundwater to climate-induced pumping variability. *Nature Geoscience*, **10** (2), 105–108. https://doi.org/10.1038/ngeo2883

47. Condon, L.E. and R.M. Maxwell, 2019: Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion. *Science Advances*, **5** (6), 4574. https://doi.org/10.1126/sciadv.aav4574

48. Jasechko, S., H. Seybold, D. Perrone, Y. Fan, and J.W. Kirchner, 2021: Widespread potential loss of streamflow into underlying aquifers across the USA. *Nature*, **591** (7850), 391–395. https://doi.org/10.1038/s41586-021-03311-x

49. Lovelace, J.K., M.G. Nielsen, A.L. Read, C.J. Murphy, and M.A. Maupin, 2020: Estimated Groundwater Withdrawals from Principal Aquifers in the United States, 2015. Circular 1464. U.S. Geological Survey, Reston, VA, 70 pp. https://doi.org/10.3133/cir1464

50. Meixner, T., A.H. Manning, D.A. Stonestrom, D.M. Allen, H. Ajami, K.W. Blasch, A.E. Brookfield, C.L. Castro, J.F. Clark, D.J. Gochis, A.L. Flint, K.L. Neff, R. Niraula, M. Rodell, B.R. Scanlon, K. Singha, and M.A. Walvoord, 2016: Implications of projected climate change for groundwater recharge in the western United States. *Journal of Hydrology*, **534**, 124–138. https://doi.org/10.1016/j.jhydrol.2015.12.027

51. Niraula, R., T. Meixner, F. Dominguez, N. Bhattarai, M. Rodell, H. Ajami, D. Gochis, and C. Castro, 2017: How might recharge change under projected climate change in the western U.S.? *Geophysical Research Letters*, **44** (20), 10407–10418. https://doi.org/10.1002/2017gl075421

52. Alam, S., M. Gebremichael, R. Li, J. Dozier, and D.P. Lettenmaier, 2019: Climate change impacts on groundwater storage in the Central Valley, California. *Climatic Change*, **157** (3), 387–406. https://doi.org/10.1007/s10584-019-02585-5

53. Taylor, R., 2014: When wells run dry. *Nature*, **516** (7530), 179–180. https://doi.org/10.1038/516179a

54. Wada, Y. and M.F.P. Bierkens, 2014: Sustainability of global water use: Past reconstruction and future projections. *Environmental Research Letters*, **9** (10), 104003. https://doi.org/10.1088/1748-9326/9/10/104003

55. Hanson, R.T., L.E. Flint, A.L. Flint, M.D. Dettinger, C.C. Faunt, D. Cayan, and W. Schmid, 2012: A method for physically based model analysis of conjunctive use in response to potential climate changes. *Water Resources Research*, **48** (6). https://doi.org/10.1029/2011wr010774

56. Scanlon, B.R., C.C. Faunt, L. Longuevergne, R.C. Reedy, W.M. Alley, V.L. McGuire, and P.B. McMahon, 2012: Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (24), 9320–9325. https://doi.org/10.1073/pnas.1200311109

57. Dudley, R.W., G.A. Hodgkins, M.R. McHale, M.J. Kolian, and B. Renard, 2017: Trends in snowmelt-related streamflow timing in the conterminous United States. *Journal of Hydrology*, **547**, 208–221. https://doi.org/10.1016/j.jhydrol.2017.01.051

58. Das, T., D.W. Pierce, D.R. Cayan, J.A. Vano, and D.P. Lettenmaier, 2011: The importance of warm season warming to western U.S. streamflow changes. *Geophysical Research Letters*, **38** (23). https://doi.org/10.1029/2011gl049660

59. Chegwidden, O.S., D.E. Rupp, and B. Nijssen, 2020: Climate change alters flood magnitudes and mechanisms in climatically-diverse headwaters across the northwestern United States. *Environmental Research Letters*, **15** (9), 094048. https://doi.org/10.1088/1748-9326/ab986f

60. Naz, B.S., S.-C. Kao, M. Ashfaq, H. Gao, D. Rastogi, and S. Gangrade, 2018: Effects of climate change on streamflow extremes and implications for reservoir inflow in the United States. *Journal of Hydrology*, **556**, 359–370. https://doi.org/10.1016/j.jhydrol.2017.11.027

61. England Jr., J.F., T.A. Cohn, B.A. Faber, J.R. Stedinger, W.O. Thomas Jr., A.G. Veilleux, J.E. Kiang, and R.R. Mason Jr., 2019: Guidelines for Determining Flood Flow Frequency—Bulletin 17C. Techniques and Methods, book 4, chap. B5. U.S. Geological Survey, Reston, VA, 148 pp. https://doi.org/10.3133/tm4b5

62. Serinaldi, F. and C.G. Kilsby, 2015: Stationarity is undead: Uncertainty dominates the distribution of extremes. *Advances in Water Resources*, **77**, 17–36. https://doi.org/10.1016/j.advwatres.2014.12.013

63. Sivapalan, M. and J.M. Samuel, 2009: Transcending limitations of stationarity and the return period: Process-based approach to flood estimation and risk assessment. *Hydrological Processes*, **23** (11), 1671–1675. https://doi.org/10.1002/hyp.7292

64. Yu, G., D.B. Wright, Z. Zhu, C. Smith, and K.D. Holman, 2019: Process-based flood frequency analysis in an agricultural watershed exhibiting nonstationary flood seasonality. *Hydrology and Earth System Sciences*, **23** (5), 2225–2243. https://doi.org/10.5194/hess-23-2225-2019

65. Hodgkins, G.A., R.W. Dudley, S.A. Archfield, and B. Renard, 2019: Effects of climate, regulation, and urbanization on historical flood trends in the United States. *Journal of Hydrology*, **573**, 697–709. https://doi.org/10.1016/j.jhydrol.2019.03.102

66. Yu, G., D.B. Wright, and Z. Li, 2020: The upper tail of precipitation in convection-permitting regional climate models and their utility in nonstationary rainfall and flood frequency analysis. *Earth's Future*, **8** (10), e2020EF001613. https://doi.org/10.1029/2020ef001613

67. Grillakis, M.G., A.G. Koutroulis, J. Komma, I.K. Tsanis, W. Wagner, and G. Blöschl, 2016: Initial soil moisture effects on flash flood generation–A comparison between basins of contrasting hydro-climatic conditions. *Journal of Hydrology*, **541**, 206–217. https://doi.org/10.1016/j.jhydrol.2016.03.007

68. Sharma, A., C. Wasko, and D.P. Lettenmaier, 2018: If precipitation extremes are increasing, why aren't floods? *Water Resources Research*, **54** (11), 8545–8551. https://doi.org/10.1029/2018wr023749

69. Wasko, C. and R. Nathan, 2019: Influence of changes in rainfall and soil moisture on trends in flooding. *Journal of Hydrology*, **575**, 432–441. https://doi.org/10.1016/j.jhydrol.2019.05.054

70. Il Jeong, D. and L. Sushama, 2018: Rain-on-snow events over North America based on two Canadian regional climate models. *Climate Dynamics*, **50** (1), 303–316. https://doi.org/10.1007/s00382-017-3609-x

71. Musselman, K.N., F. Lehner, K. Ikeda, M.P. Clark, A.F. Prein, C. Liu, M. Barlage, and R. Rasmussen, 2018: Projected increases and shifts in rain-on-snow flood risk over western North America. *Nature Climate Change*, **8** (9), 808–812. https://doi.org/10.1038/s41558-018-0236-4

72. Ebel, B.A., 2020: Temporal evolution of measured and simulated infiltration following wildfire in the Colorado Front Range, USA: Shifting thresholds of runoff generation and hydrologic hazards. *Journal of Hydrology*, **585**, 124765. https://doi.org/10.1016/j.jhydrol.2020.124765

73. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. https://doi.org/10.1038/s41558-022-01290-z

74. Hettiarachchi, S., C. Wasko, and A. Sharma, 2018: Increase in flood risk resulting from climate change in a developed urban watershed—The role of storm temporal patterns. *Hydrology and Earth System Sciences*, **22** (3), 2041–2056. https://doi.org/10.5194/hess-22-2041-2018

75. Hobbins, M., I. Rangwala, J. Barsugli, and C. Dewes, 2019: Ch. 25. Extremes in evaporative demand and their implications for droughts and drought monitoring in the 21st century. In: *Extreme Hydrology and Climate Variability*. Melesse, A.M., W. Abtew, and G. Senay, Eds. Elsevier, 325–341. https://doi.org/10.1016/b978-0-12-815998-9.00025-7

76. Overpeck, J.T. and B. Udall, 2020: Climate change and the aridification of North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (22), 11856–11858. https://doi.org/10.1073/pnas.2006323117

77. Fosu, B.O., S.-Y. Simon Wang, and J.-H. Yoon, 2016: The 2014/15 snowpack drought in Washington State and its climate forcing. *Bulletin of the American Meteorological Society*, **97** (12), S19–S24. https://doi.org/10.1175/bams-d-16-0154.1

78. Belmecheri, S., F. Babst, E.R. Wahl, D.W. Stahle, and V. Trouet, 2016: Multi-century evaluation of Sierra Nevada snowpack. *Nature Climate Change*, **6** (1), 2–3. https://doi.org/10.1038/nclimate2809

79. Margulis, S.A., G. Cortés, M. Girotto, L.S. Huning, D. Li, and M. Durand, 2016: Characterizing the extreme 2015 snowpack deficit in the Sierra Nevada (USA) and the implications for drought recovery. *Geophysical Research Letters*, **43** (12), 6341–6349. https://doi.org/10.1002/2016gl068520

80. Carlton, J., 2015: Snow drought saps Washington state's economy. *Wall Street Journal*, July 1, 2015. https://www.wsj.com/articles/snow-drought-saps-washington-states-economy-1435801630

81. Sugg, Z.P., 2018: An equity autopsy: Exploring the role of water rights in water allocations and impacts for the Central Valley Project during the 2012–2016 California drought. *Resources*, **7** (1), 12. https://doi.org/10.3390/resources7010012

82. Davenport, F.V., M. Burke, and N.S. Diffenbaugh, 2021: Contribution of historical precipitation change to US flood damages. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (4), e2017524118. https://doi.org/10.1073/pnas.2017524118

83. Alaoui, A., M. Rogger, S. Peth, and G. Blöschl, 2018: Does soil compaction increase floods? A review. *Journal of Hydrology*, **557**, 631–642. https://doi.org/10.1016/j.jhydrol.2017.12.052

84. Mississippi River Commission, 2012: 2011 Mississippi River and Tributaries Flood Report. Mississippi River Commission, 45 pp. https://www.mvd.usace.army.mil/portals/52/docs/mrc/mrc_2011_flood_report.pdf

85. Harris, A.R., E.N. Fidan, N.G. Nelson, R.E. Emanuel, T. Jass, S. Kathariou, J. Niedermeyer, M. Sharara, F.L. de los Reyes, D.A. Riveros-Iregui, and J.R. Stewart, 2021: Microbial contamination in environmental waters of rural and agriculturally-dominated landscapes following Hurricane Florence. *ACS ES&T Water*, **1** (9), 2012–2019. https://doi.org/10.1021/acsestwater.1c00103

86. Schaffer-Smith, D., S.W. Myint, R.L. Muenich, D. Tong, and J.E. DeMeester, 2020: Repeated hurricanes reveal risks and opportunities for social-ecological resilience to flooding and water quality problems. *Environmental Science & Technology*, **54** (12), 7194–7204. https://doi.org/10.1021/acs.est.9b07815

87. ASCE, 2021: A Comprehensive Assessment of America's Infrastructure: 2021 Report Card for America's Infrastructure. American Society of Civil Engineers. https://infrastructurereportcard.org/

88. Roseboro, A., M.N. Torres, Z. Zhu, and A.J. Rabideau, 2021: The impacts of climate change and porous pavements on combined sewer overflows: A case study of the city of Buffalo, New York, USA. *Frontiers in Water*, **3**, 725174. https://doi.org/10.3389/frwa.2021.725174

89. National Academies of Sciences, Engineering, and Medicine, 2019: *Framing the Challenge of Urban Flooding in the United States*. The National Academies Press, Washington, DC, 100 pp. https://doi.org/10.17226/25381

90. Pieper, K.J., C.N. Jones, W.J. Rhoads, M. Rome, D.M. Gholson, A. Katner, D.E. Boellstorff, and R.E. Beighley, 2021: Microbial contamination of drinking water supplied by private wells after Hurricane Harvey. *Environmental Science & Technology*, **55** (12), 8382–8392. https://doi.org/10.1021/acs.est.0c07869

91. Wells, M.L., B. Karlson, A. Wulff, R. Kudela, C. Trick, V. Asnaghi, E. Berdalet, W. Cochlan, K. Davidson, M. De Rijcke, S. Dutkiewicz, G. Hallegraeff, K.J. Flynn, C. Legrand, H. Paerl, J. Silke, S. Suikkanen, P. Thompson, and V.L. Trainer, 2020: Future HAB science: Directions and challenges in a changing climate. *Harmful Algae*, **91**, 101632. https://doi.org/10.1016/j.hal.2019.101632

92. AghaKouchak, A., A. Mirchi, K. Madani, G. Di Baldassarre, A. Nazemi, A. Alborzi, H. Anjileli, M. Azarderakhsh, F. Chiang, E. Hassanzadeh, L.S. Huning, I. Mallakpour, A. Martinez, O. Mazdiyasni, H. Moftakhari, H. Norouzi, M. Sadegh, D. Sadeqi, A.F. Van Loon, and N. Wanders, 2021: Anthropogenic drought: Definition, challenges, and opportunities. *Reviews of Geophysics*, **59** (2), e2019RG000683. https://doi.org/10.1029/2019rg000683

93. Crausbay, S.D., J. Betancourt, J. Bradford, J. Cartwright, W.C. Dennison, J. Dunham, C.A.F. Enquist, A.G. Frazier, K.R. Hall, J.S. Littell, C.H. Luce, R. Palmer, A.R. Ramirez, I. Rangwala, L. Thompson, B.M. Walsh, and S. Carter, 2020: Unfamiliar territory: Emerging themes for ecological drought research and management. *One Earth*, **3** (3), 337–353. https://doi.org/10.1016/j.oneear.2020.08.019

94. Mankin, J.S., I. Simpson, A. Hoell, R. Fu, J. Lisonbee, A. Sheffield, and D. Barrie, 2021: NOAA Drought Task Force Report on the 2020–2021 Southwestern U.S. Drought. National Oceanic and Atmospheric Administration Drought Task Force, Modeling, Analysis, Predictions, and Projections Program, and National Integrated Drought Information System. https://www.drought.gov/documents/noaa-drought-task-force-report-2020-2021-southwestern-us-drought

95. Overpeck, J.T., 2013: The challenge of hot drought. *Nature*, **503** (7476), 350–351. https://doi.org/10.1038/503350a

96. Otkin, J.A., M. Woloszyn, H. Wang, M. Svoboda, M. Skumanich, R. Pulwarty, J. Lisonbee, A. Hoell, M. Hobbins, T. Haigh, and A.E. Cravens, 2022: Getting ahead of flash drought: From early warning to early action. *Bulletin of the American Meteorological Society*, **103** (10), E2188–E2202. https://doi.org/10.1175/bams-d-21-0288.1

97. Svoboda, M., D. LeComte, M. Hayes, R. Heim, K. Gleason, J. Angel, B. Rippey, R. Tinker, M. Palecki, D. Stooksbury, D. Miskus, and S. Stephens, 2002: The Drought Monitor. *Bulletin of the American Meteorological Society*, **83** (8), 1181–1190. https://doi.org/10.1175/1520-0477-83.8.1181

98. Cook, B.I., J.E. Smerdon, E.R. Cook, A.P. Williams, K.J. Anchukaitis, J.S. Mankin, K. Allen, L. Andreu-Hayles, T.R. Ault, S. Belmecheri, S. Coats, B. Coulthard, B. Fosu, P. Grierson, D. Griffin, D.A. Herrera, M. Ionita, F. Lehner, C. Leland, K. Marvel, M.S. Morales, V. Mishra, J. Ngoma, H.T.T. Nguyen, A. O'Donnell, J. Palmer, M.P. Rao, M. Rodriguez-Caton, R. Seager, D.W. Stahle, S. Stevenson, U.K. Thapa, A.M. Varuolo-Clarke, and E.K. Wise, 2022: Megadroughts in the Common Era and the Anthropocene. *Nature Reviews Earth & Environment*, **3**, 735–745. https://doi.org/10.1038/s43017-022-00329-1

99. Gangopadhyay, S., C.A. Woodhouse, G.J. McCabe, C.C. Routson, and D.M. Meko, 2022: Tree rings reveal unmatched 2nd century drought in the Colorado River Basin. *Geophysical Research Letters*, **49** (11), e2022GL098781. https://doi.org/10.1029/2022gl098781

100. Lachniet, M.S., 2020: Illuminating the meaning of Asian monsoon cave speleothem records. *Paleoceanography and Paleoclimatology*, **35** (1), e2019PA003841. https://doi.org/10.1029/2019pa003841

101. Martin, J.T., G.T. Pederson, C.A. Woodhouse, E.R. Cook, G.J. McCabe, K.J. Anchukaitis, E.K. Wise, P.J. Erger, L. Dolan, M. McGuire, S. Gangopadhyay, K.J. Chase, J.S. Littell, S.T. Gray, S. St. George, J.M. Friedman, D.J. Sauchyn, J.-M. St-Jacques, and J. King, 2020: Increased drought severity tracks warming in the United States' largest river basin. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (21), 11328–11336. https://doi.org/10.1073/pnas.1916208117

102. Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, J.T. Abatzoglou, K. Bolles, S.H. Baek, A.M. Badger, and B. Livneh, 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368** (6488), 314–318. https://doi.org/10.1126/science.aaz9600

103. Boyer, J.S., P. Byrne, K.G. Cassman, M. Cooper, D. Delmer, T. Greene, F. Gruis, J. Habben, N. Hausmann, N. Kenny, R. Lafitte, S. Paszkiewicz, D. Porter, A. Schlegel, J. Schussler, T. Setter, J. Shanahan, R.E. Sharp, T.J. Vyn, D. Warner, and J. Gaffney, 2013: The U.S. drought of 2012 in perspective: A call to action. *Global Food Security*, **2** (3), 139–143. https://doi.org/10.1016/j.gfs.2013.08.002

104. Van Loon, A.F., 2015: Hydrological drought explained. *WIREs Water*, **2** (4), 359–392. https://doi.org/10.1002/wat2.1085

105. Turner, S.W., N. Voisin, K.D. Nelson, and V.C. Tidwell, 2022: Drought Impacts on Hydroelectric Power Generation in the Western United States: A Multiregional Analysis of 21st Century Hydropower Generation. PNNL-33212. U.S. Department of Energy, Pacific Northwest National Laboratory, Richland, WA. https://doi.org/10.2172/1887470

106. Crausbay, S.D., A.R. Ramirez, S.L. Carter, M.S. Cross, K.R. Hall, D.J. Bathke, J.L. Betancourt, S. Colt, A.E. Cravens, M.S. Dalton, J.B. Dunham, L.E. Hay, M.J. Hayes, J. McEvoy, C.A. McNutt, M.A. Moritz, K.H. Nislow, N. Raheem, and T. Sanford, 2017: Defining ecological drought for the twenty-first century. *Bulletin of the American Meteorological Society*, **98** (12), 2543–2550. https://doi.org/10.1175/bams-d-16-0292.1

107. EcoAdapt, 2021: Freshwater Marshes, Wetlands, and Ponds: Climate Change Vulnerability Assessment Summary for the Santa Cruz Mountains Climate Adaptation Project. EcoAdapt, Bainbridge Island, WA, 7 pp. https://ecoadapt.org/data/documents/EcoAdapt_SantaCruzMtnsVASummary_Freshwatermarsheswetlandsandponds_FINAL_Mar2021.pdf

108. Poff, B., K.A. Koestner, D.G. Neary, and D. Merritt, 2012: Threats to Western United States Riparian Ecosystems: A Bibliography. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 78 pp. https://doi.org/10.2737/rmrs-gtr-269

109. Vose, J.M., J.S. Clark, C.H. Luce, and T. Patel-Weynand, 2016: Effects of Drought on Forests and Rangelands in the United States: A Comprehensive Science Synthesis. Gen. Tech. Rep. WO-93b. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 289 pp. https://doi.org/10.2737/wo-gtr-93b

110. Höök, T.O., C.J. Foley, P. Collingsworth, L. Dorworth, B. Fisher, J.T. Hoverman, E. LaRue, M. Pyron, and J. Tank, 2020: An assessment of the potential impacts of climate change on freshwater habitats and biota of Indiana, USA. *Climatic Change*, **163** (4), 1897–1916. https://doi.org/10.1007/s10584-019-02502-w

111. Johnson, W.C., B. Werner, and G.R. Guntenspergen, 2016: Non-linear responses of glaciated prairie wetlands to climate warming. *Climatic Change*, **134** (1), 209–223. https://doi.org/10.1007/s10584-015-1534-8

112. Riedel, T., 2019: Temperature-associated changes in groundwater quality. *Journal of Hydrology*, **572**, 206–212. https://doi.org/10.1016/j.jhydrol.2019.02.059

113. Bloomfield, J.P., B.P. Marchant, and A.A. McKenzie, 2019: Changes in groundwater drought associated with anthropogenic warming. *Hydrology and Earth System Sciences*, **23** (3), 1393–1408. https://doi.org/10.5194/hess-23-1393-2019

114. Galloway, D.L., D. R. Jones, and S.E. Ingebritsen, 1999: Land Subsidence in the United States. USGS Numbered Series 1182. U.S. Geological Survey, 177 pp. https://doi.org/10.3133/cir1182

115. Borunda, A., 2019: We pump too much water out of the ground—And that's killing our rivers. *National Geographic*. https://www.nationalgeographic.com/science/article/groundwater-pumping-killing-rivers-streams

116. CJWG, 2017: Advancing Climate Justice in California: Guiding Principles and Recommendations for Policy and Funding Decisions. California Climate Justice Working Group. https://www.healthyworldforall.org/en/express-img/17081516-3570-img1.pdf

117. Goldsmith, L., V. Raditz, and M. Méndez, 2022: Queer and present danger: Understanding the disparate impacts of disasters on LGBTQ+ communities. *Disasters*, **46** (4), 946–973. https://doi.org/10.1111/disa.12509

118. Nelson, M., R. Ehrenfeucht, T. Birch, and A. Brand, 2022: Getting by and getting out: How residents of Louisiana's frontline communities are adapting to environmental change. *Housing Policy Debate*, **32** (1), 84–101. https://doi.org/10.1080/10511482.2021.1925944

119. Edmonds, D.A., R.L. Caldwell, E.S. Brondizio, and S.M.O. Siani, 2020: Coastal flooding will disproportionately impact people on river deltas. *Nature Communications*, **11** (1), 4741. https://doi.org/10.1038/s41467-020-18531-4

120. Reckien, D., F. Creutzig, B. Fernandez, S. Lwasa, M. Tovar-Restrepo, D. Mcevoy, and D. Satterthwaite, 2017: Climate change, equity and the Sustainable Development Goals: An urban perspective. *Environment and Urbanization*, **29** (1), 159–182. https://doi.org/10.1177/0956247816677778

121. Thiault, L., C. Mora, J.E. Cinner, W.W.L. Cheung, N.A.J. Graham, F.A. Januchowski-Hartley, D. Mouillot, U.R. Sumaila, and J. Claudet, 2019: Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries. *Science Advances*, **5** (11), 9976. https://doi.org/10.1126/sciadv.aaw9976

122. Ebi, K.L., J. Vanos, J.W. Baldwin, J.E. Bell, D.M. Hondula, N.A. Errett, K. Hayes, C.E. Reid, S. Saha, J. Spector, and P. Berry, 2021: Extreme weather and climate change: Population health and health system implications. *Annual Review of Public Health*, **42** (1), 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

123. EPA, 2022: Climate Change and Human Health: Who's Most at Risk? U.S. Environmental Protection Agency, accessed March 20, 2022. https://www.epa.gov/climate-change/climate-change-and-human-health-whos-most-risk

124. Leffers, J.M., 2022: Climate change and health of children: Our borrowed future. *Journal of Pediatric Health Care*, **36** (1), 12–19. https://doi.org/10.1016/j.pedhc.2021.09.002

125. Bronen, R., J. Maldonado, E. Marino, and P. Hardison, 2018: Ch. 12. Climate change and displacement: Challenges and needs to address an imminent reality. In: *Challenging the Prevailing Paradigm of Displacement and Resettlement: Risks, Impoverishment, Legacies, Solutions*. Cernea, M.M. and J.K. Maldonado, Eds. Routledge, London, UK, 252–272. https://doi.org/10.4324/9781315163062

126. MacDonald, J.P., A.C. Willox, J.D. Ford, I. Shiwak, and M. Wood, 2015: Protective factors for mental health and well-being in a changing climate: Perspectives from Inuit youth in Nunatsiavut, Labrador. *Social Science & Medicine*, **141**, 133–141. https://doi.org/10.1016/j.socscimed.2015.07.017

127. Marino, E., 2015: *Fierce Climate, Sacred Ground: An Ethnography of Climate Change in Shishmaref, Alaska*. University of Alaska Press, Fairbanks, AK, 122 pp. https://upcolorado.com/university-of-alaska-press/item/5674-fierce-climate-sacred-ground

128. Tate, E., M.A. Rahman, C.T. Emrich, and C.C. Sampson, 2021: Flood exposure and social vulnerability in the United States. *Natural Hazards*, **106** (1), 435–457. https://doi.org/10.1007/s11069-020-04470-2

129. Titus, J.G., 2023: Population in floodplains or close to sea level increased in US but declined in some counties—Especially among black residents. *Environmental Research Letters*, **18** (3), 034001. https://doi.org/10.1088/1748-9326/acadf5

130. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

131. Engström, J., K. Jafarzadegan, and H. Moradkhani, 2020: Drought vulnerability in the United States: An integrated assessment. *Water*, **12** (7), 2033. https://doi.org/10.3390/w12072033

132. NHC, 2018: Costliest U.S. Tropical Cyclones Tables Updated. National Oceanic and Atmospheric Administration, National Weather Service, National Hurricane Center, Miami, FL, 3 pp. https://www.nhc.noaa.gov/news/UpdatedCostliest.pdf

133. Risser, M.D. and M.F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophysical Research Letters*, **44** (24), 12457–12464. https://doi.org/10.1002/2017gl075888

134. van Oldenborgh, G.J., K. van der Wiel, A. Sebastian, R. Singh, J. Arrighi, F. Otto, K. Haustein, S. Li, G. Vecchi, and H. Cullen, 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12** (12), 124009. https://doi.org/10.1088/1748-9326/aa9ef2

135. Wang, S.Y.S., L. Zhao, J.-H. Yoon, P. Klotzbach, and R.R. Gillies, 2018: Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas. *Environmental Research Letters*, **13** (5), 054014. https://doi.org/10.1088/1748-9326/aabb85

136. Wehner, M. and C. Sampson, 2021: Attributable human-induced changes in the magnitude of flooding in the Houston, Texas region during Hurricane Harvey. *Climatic Change*, **166** (1), 1–13. https://doi.org/10.1007/s10584-021-03114-z

137. Smiley, K.T., I. Noy, M.F. Wehner, D. Frame, C.C. Sampson, and O.E.J. Wing, 2022: Social inequalities in climate change-attributed impacts of Hurricane Harvey. *Nature Communications*, **13** (1), 3418. https://doi.org/10.1038/s41467-022-31056-2

138. Smiley, K.T., 2020: Social inequalities in flooding inside and outside of floodplains during Hurricane Harvey. *Environmental Research Letters*, **15** (9), 0940b3. https://doi.org/10.1088/1748-9326/aba0fe

139. Chakraborty, J., S.E. Grineski, and T.W. Collins, 2019: Hurricane Harvey and people with disabilities: Disproportionate exposure to flooding in Houston, Texas. *Social Science & Medicine*, **226**, 176–181. https://doi.org/10.1016/j.socscimed.2019.02.039

140. Chakraborty, J., A.A. McAfee, T.W. Collins, and S.E. Grineski, 2021: Exposure to Hurricane Harvey flooding for subsidized housing residents of Harris County, Texas. *Natural Hazards*, **106** (3), 2185–2205. https://doi.org/10.1007/s11069-021-04536-9

141. Vacs Renwick, D., A. Heinrich, R. Weisman, H. Arvanaghi, and K. Rotert, 2019: Potential public health impacts of deteriorating distribution system infrastructure. *Journal-American Water Works Association*, **111** (2), 42–53. https://doi.org/10.1002/awwa.1235

142. Mueller, J.T. and S. Gasteyer, 2021: The widespread and unjust drinking water and clean water crisis in the United States. *Nature Communications*, **12** (1), 3544. https://doi.org/10.1038/s41467-021-23898-z

143. Cozzetto, K., K. Chief, K. Dittmer, M. Brubaker, R. Gough, K. Souza, F. Ettawageshik, S. Wotkyns, S. Opitz-Stapleton, S. Duren, and P. Chavan, 2014: Ch. 6. Climate change impacts on the water resources of American Indians and Alaska Natives in the U.S. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., R.E. Pandya, and B.J. Colombi, Eds. Springer, Cham, Switzerland, 61–76. https://doi.org/10.1007/978-3-319-05266-3_6

144. NCAI, 2017: Tribal Infrastructure: Investing in Indian Country for a Stronger America. National Congress of American Indians, Washington, DC. http://www.ncai.org/ncai-infrastructurereport-final.pdf

145. Tanana, H., J. Combs, and A. Hoss, 2021: Water is life: Law, systemic racism, and water security in Indian Country. *Health Security*, **19** (1), 78–82. https://doi.org/10.1089/hs.2021.0034

146. IHS, 2019: Annual Report to the Congress of the United States on Sanitation Deficiency Levels for Indian Homes and Communities. Indian Health Service, Office of Environmental Health and Engineering. https://www.ihs.gov/sites/newsroom/themes/responsive2017/display_objects/documents/FY_2019_RTC_Sanitation_Deficiencies_Report.pdf

147. Anderson, E.P., S. Jackson, R.E. Tharme, M. Douglas, J.E. Flotemersch, M. Zwarteveen, C. Lokgariwar, M. Montoya, A. Wali, G.T. Tipa, T.D. Jardine, J.D. Olden, L. Cheng, J. Conallin, B. Cosens, C. Dickens, D. Garrick, D. Groenfeldt, J. Kabogo, D.J. Roux, A. Ruhi, and A.H. Arthington, 2019: Understanding rivers and their social relations: A critical step to advance environmental water management. *WIREs Water*, **6** (6), e1381. https://doi.org/10.1002/wat2.1381

148. Carey, J., 2020: Managed retreat increasingly seen as necessary in response to climate change's fury. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (24), 13182–13185. https://doi.org/10.1073/pnas.2008198117

149. Li, J. and K. Spidalieri, 2021: Home is where the safer ground is: The need to promote affordable housing laws and policies in receiving communities. *Journal of Environmental Studies and Sciences*, **11** (4), 682–695. https://doi.org/10.1007/s13412-021-00702-4

150. ASFPM, 2014: No Adverse Impact Planning How-To Guide. Association of State Floodplain Managers. https://asfpm-library.s3-us-west-2.amazonaws.com/FSC/NAI/ASFPM_NAI_Planning_2014.pdf

151. Chang, S., W. Graham, J. Geurink, N. Wanakule, and T. Asefa, 2018: Evaluation of impacts of future climate change and water use scenarios on regional hydrology. *Hydrology and Earth System Sciences*, **22** (9), 4793–4813. https://doi.org/10.5194/hess-22-4793-2018

152. SNWA, 2019: Joint Water Conservation Plan. Southern Nevada Water Authority. https://www.snwa.com/assets/pdf/reports-conservation-plan-2019.pdf

153. Smith, R., E. Zagona, J. Kasprzyk, N. Bonham, E. Alexander, A. Butler, J. Prairie, and C. Jerla, 2022: Decision science can help address the challenges of long-term planning in the Colorado River Basin. *Journal of the American Water Resources Association*, **58** (5), 735–745. https://doi.org/10.1111/1752-1688.12985

154. Woodhouse, C.A., R.M. Smith, S.A. McAfee, G.T. Pederson, G.J. McCabe, W.P. Miller, and A. Csank, 2021: Upper Colorado River Basin 20th century droughts under 21st century warming: Plausible scenarios for the future. *Climate Services*, **21**, 100206. https://doi.org/10.1016/j.cliser.2020.100206

155. Fleming, S.W., D.C. Garen, A.G. Goodbody, C.S. McCarthy, and L.C. Landers, 2021: Assessing the new Natural Resources Conservation Service water supply forecast model for the American West: A challenging test of explainable, automated, ensemble artificial intelligence. *Journal of Hydrology*, **602**, 126782. https://doi.org/10.1016/j.jhydrol.2021.126782

156. Goharian, E., S.J. Burian, and M. Karamouz, 2018: Using joint probability distribution of reliability and vulnerability to develop a water system performance index. *Journal of Water Resources Planning and Management*, **144** (2), 04017081. https://doi.org/10.1061/(asce)wr.1943-5452.0000869

157. Steinschneider, S., R. McCrary, S. Wi, K. Mulligan, L.O. Mearns, and C. Brown, 2015: Expanded decision-scaling framework to select robust long-term water-system plans under hydroclimatic uncertainties. *Journal of Water Resources Planning and Management*, **141** (11), 04015023. https://doi.org/10.1061/(asce)wr.1943-5452.0000536

158. Towler, E., D. Woodson, S. Baker, M. Ge, J. Prairie, B. Rajagopalan, S. Shanahan, and R. Smith, 2022: Incorporating mid-term temperature predictions into streamflow forecasts and operational reservoir projections in the Colorado River Basin. *Journal of Water Resources Planning and Management*, **148** (4), 04022007. https://doi.org/10.1061/(asce)wr.1943-5452.0001534

159. Kim, Y., T. Carvalhaes, A. Helmrich, S. Markolf, R. Hoff, M. Chester, R. Li, and N. Ahmad, 2022: Leveraging SETS resilience capabilities for safe-to-fail infrastructure under climate change. *Current Opinion in Environmental Sustainability*, **54**, 101153. https://doi.org/10.1016/j.cosust.2022.101153

160. Kim, Y., D.A. Eisenberg, E.N. Bondank, M.V. Chester, G. Mascaro, and B.S. Underwood, 2017: Fail-safe and safe-to-fail adaptation: Decision-making for urban flooding under climate change. *Climatic Change*, **145** (3), 397–412. https://doi.org/10.1007/s10584-017-2090-1

161. Salinas Rodriguez, C.N.A., R. Ashley, B. Gersonius, J. Rijke, A. Pathirana, and C. Zevenbergen, 2014: Incorporation and application of resilience in the context of water-sensitive urban design: Linking European and Australian perspectives. *WIREs Water*, **1** (2), 173–186. https://doi.org/10.1002/wat2.1017

162. Gorelick, D.E., L. Lin, H.B. Zeff, Y. Kim, J.M. Vose, J.W. Coulston, D.N. Wear, L.E. Band, P.M. Reed, and G.W. Characklis, 2020: Accounting for adaptive water supply management when quantifying climate and land cover change vulnerability. *Water Resources Research*, **56** (1), e2019WR025614. https://doi.org/10.1029/2019wr025614

163. Misra, V., T. Irani, L. Staal, K. Morris, T. Asefa, C. Martinez, and W. Graham, 2021: The Florida Water and Climate Alliance (FloridaWCA): Developing a stakeholder–scientist partnership to create actionable science in climate adaptation and water resource management. *Bulletin of the American Meteorological Society*, **102** (2), 367–382. https://doi.org/10.1175/bams-d-19-0302.1

164. Kruk, M.C., B. Parker, J.J. Marra, K. Werner, R. Heim, R. Vose, and P. Malsale, 2017: Engaging with users of climate information and the coproduction of knowledge. *Weather, Climate, and Society*, **9** (4), 839–849. https://doi.org/10.1175/wcas-d-16-0127.1

165. Sullivan, A., 2022: Climate-Resilient Planning and Design Guidance: Building Our Future Today. Philadelphia Water Department, Philadelphia, PA. https://water.phila.gov/pool/files/climate-resilient-guidance.pdf

166. Vincent, K., M. Daly, C. Scannell, and B. Leathes, 2018: What can climate services learn from theory and practice of co-production? *Climate Services*, **12**, 48–58. https://doi.org/10.1016/j.cliser.2018.11.001

167. WUCA, 2021: An Enhanced Climate-Related Risks and Opportunities Framework and Guidebook for Water Utilities Preparing for a Changing Climate. Project No. 5056. Water Utility Climate Alliance. https://www.wucaonline.org/assets/pdf/project-5056-guidebook.pdf

168. Hoylman, Z.H., R.K. Bocinsky, and K.G. Jencso, 2022: Drought assessment has been outpaced by climate change: Empirical arguments for a paradigm shift. *Nature Communications*, **13** (1), 2715. https://doi.org/10.1038/s41467-022-30316-5

169. Xu, Y., V. Ramanathan, and D.G. Victor, 2018: Global warming will happen faster than we think. *Nature*, **564** (7734), 30–32. https://doi.org/10.1038/d41586-018-07586-5

170. Lopez-Cantu, T. and C. Samaras, 2018: Temporal and spatial evaluation of stormwater engineering standards reveals risks and priorities across the United States. *Environmental Research Letters*, **13** (7), 074006. https://doi.org/10.1088/1748-9326/aac696

171. Wright, D.B., C.D. Bosma, and T. Lopez-Cantu, 2019: U.S. hydrologic design standards insufficient due to large increases in frequency of rainfall extremes. *Geophysical Research Letters*, **46** (14), 8144–8153. https://doi.org/10.1029/2019gl083235

172. Brekke, L.D., J.E. Kiang, J.R. Olsen, R.S. Pulwarty, D.A. Raff, D.P. Turnipseed, R.S. Webb, and K.D. White, 2009: Climate Change and Water Resources Management: A Federal Perspective. USGS Circular 1331. U.S. Geological Survey, Reston, VA, 65 pp. http://pubs.usgs.gov/circ/1331/

173. Mulroy, P., 2017: *Water Problem: Climate Change and Water Policy in the United States*. The Brookings Institution, Washington, DC, 208 pp. https://www.brookings.edu/book/the-water-problem/

174. Olmstead, S.M., 2014: Climate change adaptation and water resource management: A review of the literature. *Energy Economics*, **46**, 500–509. https://doi.org/10.1016/j.eneco.2013.09.005

175. MacDonnell, L., 2020: Colorado River Governance: A Model? Social Science Research Network, 4 pp. https://papers.ssrn.com/abstract=3743051

176. MacDonnell, L., 2021: The Law of the Colorado River: Coping with Sever Sustained Drought, Part II. Social Science Research Network, 14 pp. https://ssrn.com/abstract=3811024

177. Fleck, J. and A. Castle, 2022: Green light for adaptive policies on the Colorado River. *Water*, **14** (1), 2. https://doi.org/10.3390/w14010002

178. Juricich, R., 2020: Colorado River Basin governance, decision making, and alternative approaches. In: *World Environmental and Water Resources Congress 2020: Water Resources Planning and Management and Irrigation and Drainage*. American Society of Civil Engineers, 121–130. https://doi.org/10.1061/9780784482957.013

179. Sullivan, A., D.D. White, and M. Hanemann, 2019: Designing collaborative governance: Insights from the drought contingency planning process for the lower Colorado River Basin. *Environmental Science and Policy*, **91**, 39–49. https://doi.org/10.1016/j.envsci.2018.10.011

180. Karambelkar, S. and A.K. Gerlak, 2020: Collaborative governance and stakeholder participation in the Colorado River Basin: An examination of patterns of inclusion and exclusion. *Natural Resources Journal*, **60** (1), 1–46. https://www.jstor.org/stable/26912770

181. Reed, T., L.R. Mason, and C.C. Ekenga, 2020: Adapting to climate change in the Upper Mississippi River Basin: Exploring stakeholder perspectives on river system management and flood risk reduction. *Environmental Health Insights*, **14**, 1178630220984153. https://doi.org/10.1177/1178630220984153

182. International Joint Commission, 2016: The Boundary Waters Treaty of 1909. International Joint Commission. https://www.ijc.org/en/boundary-waters-treaty-1909

183. International Joint Commission, 2014: Lake Ontario–St. Lawrence River Plan 2014: Protecting Against Extreme Water Levels, Restoring Wetlands and Preparing for Climate Change. International Joint Commission, Ottawa, Ontario, 98 pp. https://ijc.org/sites/default/files/IJC_LOSR_EN_Web.pdf

184. Kuhn, E. and J. Fleck, 2019: *Science Be Dammed: How Ignoring Inconvenient Science Drained the Colorado River*. University of Arizona Press, Tucson, AZ. https://uapress.arizona.edu/book/science-be-dammed

185. Lukas, J.J. and E.A. Payton, 2020: Colorado River Basin Climate and Hydrology: State of the Science. Western Water Assessment. University of Colorado Boulder, Cooperative Institute for Research in Environmental Sciences, Boulder, CO. https://doi.org/10.25810/3hcv-w477

186. Salehabadi, H., D.G. Tarboton, B. Udall, K.G. Wheeler, and J.C. Schmidt, 2022: An assessment of potential severe droughts in the Colorado River Basin. JAWRA *Journal of the American Water Resources Association*, **58** (6), 1053–1075. https://doi.org/10.1111/1752-1688.13061

187. Fillmore, H. and L. Singletary, 2021: Climate data and information needs of Indigenous communities on reservation lands: Insights from stakeholders in the Southwestern United States. *Climatic Change*, **169** (3), 37. https://doi.org/10.1007/s10584-021-03285-9

188. Conroy-Ben, O. and R. Richard, 2018: Disparities in water quality in Indian Country. *Journal of Contemporary Water Research & Education*, **163** (1), 31–44. https://doi.org/10.1111/j.1936-704x.2018.03268.x

189. Dahm, K., T. Hawbaker, R. Frus, A. Monroe, J. Bradford, W. Andrews, A. Torregrosa, E. Anderson, D. Dean, and S. Qi, 2023: Colorado River Basin Actionable and Strategic Integrated Science and Technology Project—Science Strategy. USGS Circular 1502. U.S. Geological Survey, 57 pp. https://doi.org/10.3133/cir1502

190. Margulis, S.A., Y. Fang, D. Li, D.P. Lettenmaier, and K. Andreadis, 2019: The utility of infrequent snow depth images for deriving continuous space-time estimates of seasonal snow water equivalent. *Geophysical Research Letters*, **46** (10), 5331–5340. https://doi.org/10.1029/2019gl082507

191. Painter, T.H., D.F. Berisford, J.W. Boardman, K.J. Bormann, J.S. Deems, F. Gehrke, A. Hedrick, M. Joyce, R. Laidlaw, D. Marks, C. Mattmann, B. McGurk, P. Ramirez, M. Richardson, S.M. Skiles, F.C. Seidel, and A. Winstral, 2016: The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo. *Remote Sensing of Environment*, **184**, 139–152. https://doi.org/10.1016/j.rse.2016.06.018

192. Pflug, J.M., S.A. Margulis, and J.D. Lundquist, 2022: Inferring watershed-scale mean snowfall magnitude and distribution using multidecadal snow reanalysis patterns and snow pillow observations. *Hydrological Processes*, **36** (6), e14581. https://doi.org/10.1002/hyp.14581

193. Yang, K., K.N. Musselman, K. Rittger, S.A. Margulis, T.H. Painter, and N.P. Molotch, 2022: Combining ground-based and remotely sensed snow data in a linear regression model for real-time estimation of snow water equivalent. *Advances in Water Resources*, **160**, 104075. https://doi.org/10.1016/j.advwatres.2021.104075

194. Melton, F.S., J. Huntington, R. Grimm, J. Herring, M. Hall, D. Rollison, T. Erickson, R. Allen, M. Anderson, J.B. Fisher, A. Kilic, G.B. Senay, J. Volk, C. Hain, L. Johnson, A. Ruhoff, P. Blankenau, M. Bromley, W. Carrara, B. Daudert, C. Doherty, C. Dunkerly, M. Friedrichs, A. Guzman, G. Halverson, J. Hansen, J. Harding, Y. Kang, D. Ketchum, B. Minor, C. Morton, S. Ortega-Salazar, T. Ott, M. Ozdogan, P.M. ReVelle, M. Schull, C. Wang, Y. Yang, and R.G. Anderson, 2021: OpenET: Filling a critical data gap in water management for the western United States. *JAWRA Journal of the American Water Resources Association*, **58** (6), 971–994. https://doi.org/10.1111/1752-1688.12956

195. Senay, G.B., S. Kagone, and N.M. Velpuri, 2020: Operational global actual evapotranspiration: Development, evaluation, and dissemination. *Sensors*, **20** (7), 1915. https://doi.org/10.3390/s20071915

196. Tapley, B.D., M.M. Watkins, F. Flechtner, C. Reigber, S. Bettadpur, M. Rodell, I. Sasgen, J.S. Famiglietti, F.W. Landerer, D.P. Chambers, J.T. Reager, A.S. Gardner, H. Save, E.R. Ivins, S.C. Swenson, C. Boening, C. Dahle, D.N. Wiese, H. Dobslaw, M.E. Tamisiea, and I. Velicogna, 2019: Contributions of GRACE to understanding climate change. *Nature Climate Change*, **9** (5), 358–369. https://doi.org/10.1038/s41558-019-0456-2

197. Vano, J., J. Hamman, E. Gutmann, A. Wood, N. Mizukami, M. Clark, D.W. Pierce, D.R. Cayan, C. Wobus, K. Nowak, and J. Arnold, 2020: Comparing Downscaled LOCA and BCSD CMIP5 Climate and Hydrology Projections: Release of Downscaled LOCA CMIP5 Hydrology. Bureau of Reclamation, Livermore, CA, 96 pp. https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/LOCA_BCSD_hydrology_tech_memo.pdf

198. Chapman, R.A., G.F. Midgley, and K. Smart, 2021: Diverse trends in observed pan evaporation in South Africa suggest multiple interacting drivers. *South African Journal of Science*, **117** (7/8). https://doi.org/10.17159/sajs.2021/7900

199. Hobbins, M.T., J.A. Ramírez, and T.C. Brown, 2004: Trends in pan evaporation and actual evapotranspiration across the conterminous U.S.: Paradoxical or complementary? *Geophysical Research Letters*, **31** (13). https://doi.org/10.1029/2004gl019846

200. Hodgkins, G.A., P.H. Whitfield, D.H. Burn, J. Hannaford, B. Renard, K. Stahl, A.K. Fleig, H. Madsen, L. Mediero, J. Korhonen, C. Murphy, and D. Wilson, 2017: Climate-driven variability in the occurrence of major floods across North America and Europe. *Journal of Hydrology*, **552**, 704–717. https://doi.org/10.1016/j.jhydrol.2017.07.027

201. Do, H.X., S. Westra, and M. Leonard, 2017: A global-scale investigation of trends in annual maximum streamflow. *Journal of Hydrology*, **552**, 28–43. https://doi.org/10.1016/j.jhydrol.2017.06.015

202. Milly, P.C.D., R.T. Wetherald, K.A. Dunne, and T.L. Delworth, 2002: Increasing risk of great floods in a changing climate. *Nature*, **415** (6871), 514–517. https://doi.org/10.1038/415514a

203. Hirsch, R.M. and S.A. Archfield, 2015: Not higher but more often. *Nature Climate Change*, **5** (3), 198–199. https://doi.org/10.1038/nclimate2551

204. Mallakpour, I. and G. Villarini, 2015: The changing nature of flooding across the central United States. *Nature Climate Change*, **5** (3), 250–254. https://doi.org/10.1038/nclimate2516

205. Hoerling, M., J. Eischeid, X. Quan, and A. Badger, 2019: Causes for the century-long decline in Colorado River flow. *Journal of Climate*, **32** (23), 8181–8203. https://doi.org/10.1175/jcli-d-19-0207.1

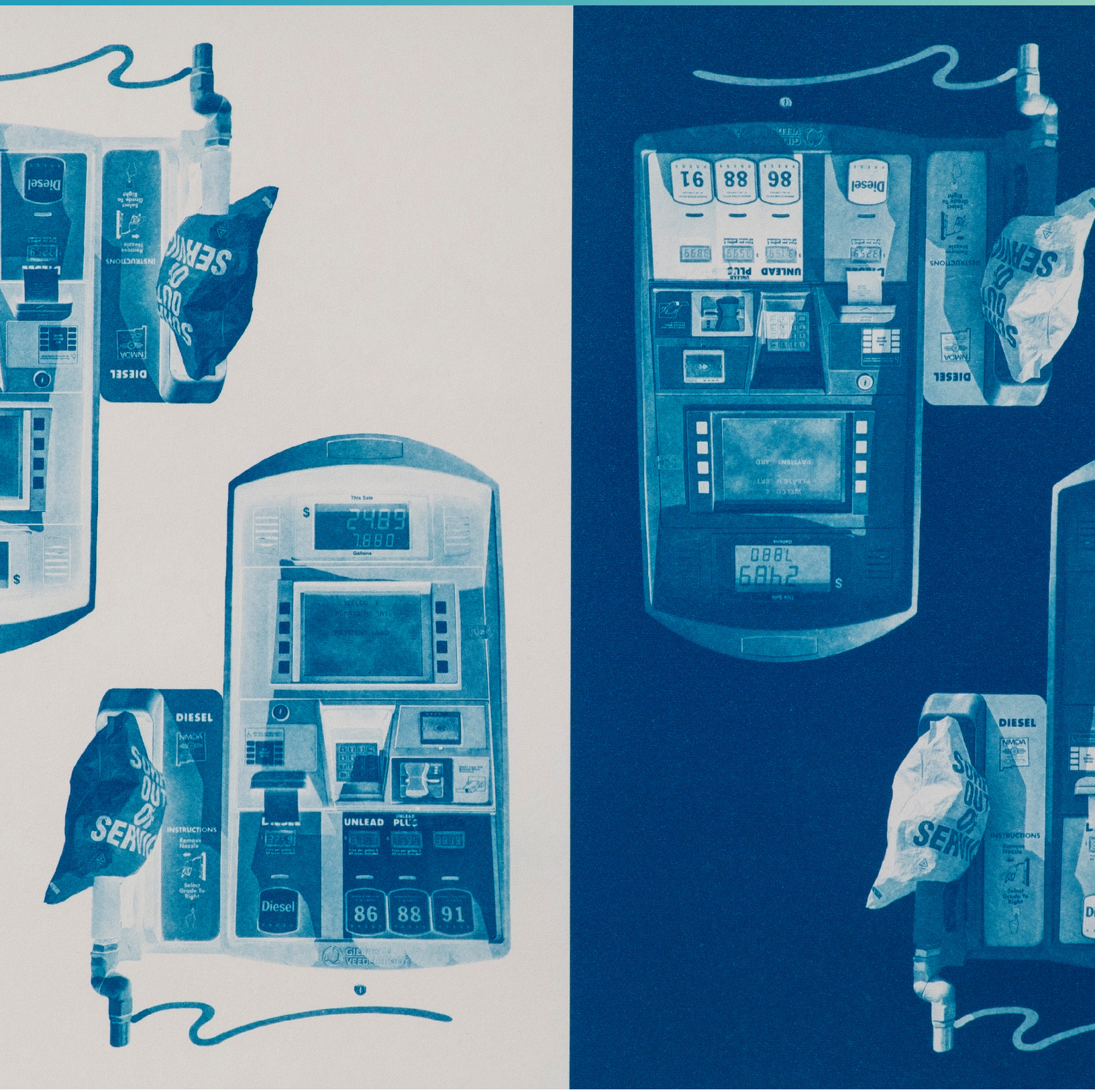
206. Milly, P.C.D. and K.A. Dunne, 2020: Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. *Science*, **367** (6483), 1252–1255. https://doi.org/10.1126/science.aay9187

207. Tanana, H., J. Garcia, A. Olaya, C. Colwyn, H. Larsen, R. Williams, and J. King, 2021: Universal Access to Clean Water for Tribes in the Colorado River Basin. Water and Tribes Initiative, Colorado River Basin. http://www.naturalresourcespolicy.org/docs/water-tribes/wti-full-report-4.21.pdf

208. Cutter, S.L., 2021: The changing nature of hazard and disaster risk in the Anthropocene. *Annals of the American Association of Geographers*, **111** (3), 819–827. https://doi.org/10.1080/24694452.2020.1744423

209. Dilling, L., A. Prakash, Z. Zommers, F. Ahmad, N. Singh, S. de Wit, J. Nalau, M. Daly, and K. Bowman, 2019: Is adaptation success a flawed concept? *Nature Climate Change*, **9** (8), 572–574. https://doi.org/10.1038/s41558-019-0539-0

# Energy Supply, Delivery, and Demand



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# Introduction

Reliable and affordable clean energy is important for quality of life, economic competitiveness, and national security. However, much of today's energy infrastructure was designed for the 20th century, making it vulnerable to climate impacts, including more frequent power and fuel interruptions, increased damages to energy infrastructure, increased energy demand and reduced supply, and cascading effects impacting other sectors, including transportation, communication, and health and safety.

Societal changes are altering vulnerabilities of energy systems and communities to climate change. Changing risks result from shifts in the energy generation mix that lower greenhouse gas (GHG) emissions; increased electrification of buildings and transportation; technological innovation creating new demands for energy; greater susceptibility of energy components to domestic and international supply chain disruptions; and an increasingly automated, interconnected system susceptible to physical and cyberattacks.

While atmospheric GHG concentrations continue growing at historically high rates due to factors such as increased global energy use, energy system decarbonization is reducing the rate of GHG emissions.[1] Demand for energy is increasing, outpacing energy efficiency improvements, and electrification is expected to grow.[2,3] Adaptation to environmental change, along with improved resilience of energy production and delivery systems to climate-related events, is underway. Energy system innovations include reductions in technology costs and operational and performance improvements for energy production, delivery, and storage; distributed generation and microgrids; demand-side management; zero-emissions buildings and vehicles; and energy-market design and governance structures.

Evolving policy focuses on a transition to net-zero energy systems and away from fossil fuels. The Bipartisan Infrastructure Law[4] and the Inflation Reduction Act (IRA)[5] are the largest investments in climate and energy in American history (Chs. 25, 32).[6,7,8] These laws prioritize investments for overburdened communities and advance the Justice40 Initiative, which commits to delivering benefits of climate, clean energy, and related federal investments to these communities.[9] State and local actions include building codes, incentives, and bans intended to encourage a shift to clean energy sources.[10,11] Progress is underway, but further actions are needed to increase the pace, scale, and scope of the energy transition to deliver more clean energy and build a more resilient energy future.

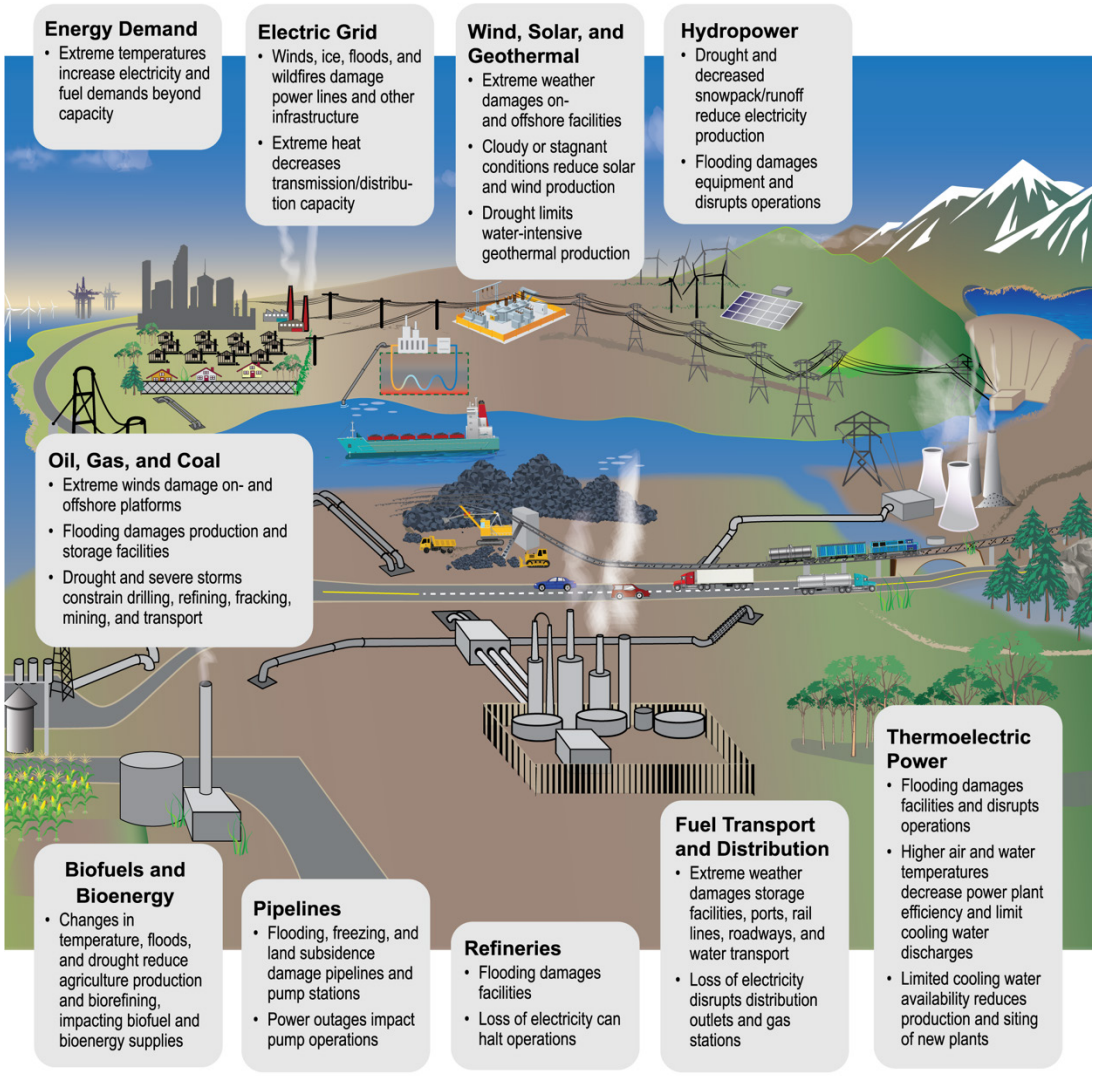
## Key Message 5.1

## Climate Change Threatens Energy Systems

Energy supply and delivery are at risk from climate-driven changes, which are also shifting demand (*virtually certain*, *very high confidence*). Climate change threats, including increases in extreme precipitation, extreme temperatures, sea level rise, and more intense storms, droughts, and wildfires, are damaging infrastructure and operations and affecting human lives and livelihoods (*virtually certain*, *very high confidence*). Impacts will vary over time and location (*virtually certain*, *very high confidence*). Without mitigation and adaptation, projected increases in the frequency, intensity, duration, and variability of extreme events will amplify effects on energy systems (*virtually certain*, *very high confidence*).

Climate change affects all aspects of the energy system—supply, delivery, and demand (Figure 5.1)—through the increased frequency, intensity, and duration of extreme events and through changing climate trends (Ch. 2). Energy production and distribution are vulnerable to flooding, hurricanes, drought, wildfires, and permafrost thaw. Extreme temperatures increase energy demands and stress electricity operations, leading to outages that disrupt societal services. The magnitudes of climate threats vary temporally and spatially (e.g., droughts and wildfires in the Southwest, hurricanes and storm surge on the Gulf and East Coasts).

## Climate Change Impacts on the Energy System




**All aspects of the US energy system are vulnerable to the effects of climate change.**

**Figure 5.1.** Climate change impacts all components of the Nation's energy system—resource extraction and processing, energy transport and storage, electricity generation, and energy end use. Adapted from DOE 2013.[12]

# Energy Supply

## Generation Systems

Sea-level rise, hurricane-force winds, and inland flooding impact coastal energy infrastructure and strategic national assets,[13,14] including the Nation's Strategic Petroleum Reserve.[15] The Gulf of Mexico region accounts for a significant portion of the Nation's crude oil production, petroleum refining, and natural gas processing capacity.[16] Coastal energy supply is especially affected by climate change and can disproportionately impact isolated and overburdened communities.[17,18]

Storm events, extreme temperature, droughts, and wildfires damage inland energy generation systems and impact operations.[19,20] Solar and wind energy generation is affected by heat, smoke, soot, and hail.[21,22,23] Flooding and freezing of extraction, storage, and distribution equipment impact natural gas production and power generation and cause power outages.[24] Extreme heat reduces the capacity and efficiency of natural gas and steam turbines.[25,26] More intense hurricanes have increased disruptions to nuclear power.[27] Drought and extreme weather can limit biofuel feedstock supplies.[28] Renewable energy will be affected by changes in wind and solar resources, although the magnitudes and locations of these effects are uncertain.[29,30,31,32,33,34] Uncertainty regarding climate impacts on wind and solar resources remains, but downscaled climate model data coupled with energy sector models are advancing.

## Electricity Generation and Water Availability

Water is used in electricity generation, including in producing hydropower and hydrogen, cooling thermoelectric generators, maintaining solar photovoltaic (PV) installations,[35] and producing feedstocks for bioenergy. Water-dependent generation is stressed by droughts,[36,37,38] snowpack depletion,[37] increases in stream temperature,[39] reservoir evaporation,[40] dam removal to restore rivers and their societal and ecological roles,[41] increasing demands for other water uses, and pumping limits that increase cost.[42]

Most of the western United States is experiencing a megadrought, disrupting water supply and hydropower generation (Ch. 2).[37,43,44] Increasing energy demand due to higher summer temperatures, coupled with a projected decrease in summer hydropower generation, will magnify the potential for energy shortfalls.[45,46]

Thermoelectric generators provide most of the Nation's electricity and rely on significant volumes of water.[47,48,49] Deployment of some low-carbon technologies, such as carbon capture, utilization, and storage (CCUS), increases this water dependence.[50] New cooling technologies for small modular reactors provide options for addressing water availability constraints.[51] The compounded impacts of decreasing summer river flows, increasing temperatures, and, in many regions, temperature limits on discharge water reduce the efficiency and generation capacity of thermoelectric generators,[52] decreasing reliability during extreme conditions.[39,53,54] Operations relying on reservoir storage for cooling water face increasing vulnerability from storage levels dropping below critical thresholds, particularly in the Southwest.[55]

# Energy Delivery

## Electricity Delivery

Power outages from extreme weather are increasing across the US. The average number of major power outages (exceeding 50,000 customers) increased by roughly 64% during 2011–2021, as compared to 2000–2010, with the most weather-related power outages attributed to extreme cold (22%), tropical cyclones (15%), and severe weather (58%).[56] Annual expenditures on electricity transmission and distribution infrastructure could rise up to 25% by 2090 under a very high scenario (RCP8.5) compared to a scenario without climate change.[57] Additional costs for power interruptions could reach $4.7 to $8.3 billion per year by 2090 (in 2022 dollars).[57]

Extreme heat events are increasing in frequency and duration (KM 2.2).[58,59] High temperatures increase powerline sagging and reduce the efficiency of transmission and distribution, stressing the grid during periods of increased demand.[57,60] Electricity infrastructure, including transformers and transmission lines, deteriorate faster in extreme temperatures, and cables have reduced carrying capacity with rising air temperature.[25,57]

Wildfires and extreme weather events pose challenges to electricity infrastructure.[61,62,63,64] Aboveground powerlines are susceptible to damage from high winds and falling vegetation.[65,66] Powerlines are also susceptible to damage and reduced efficiency from ice[67] and wildfires, including soot.[57,63,68] Flood scours, subsidence, and landslides, which increase with drought and increased groundwater pumping,[69] are damaging buried powerlines and natural gas pipelines. Coastal power substations are at risk from storm surges exacerbated by sea level rise.[70,71]

Examples of extreme-events impacts on electricity delivery include substantial damage to Puerto Rico's transmission and distribution lines after Hurricane Maria;[72] hotter and drier conditions in the Southwest enabling stronger and longer-lasting wildfires,[19] threatening the wildland–urban interface;[20] and risk of wildfires influencing utility-initiated power shutdowns in California during periods of high winds and dry conditions.[20,73,74]

## Oil and Gas Delivery

Climate change and extreme weather disrupt oil and gas supply chains.[75,76,77,78] Hurricanes, flooding, and sea level rise threaten onshore and offshore infrastructure and operations.[79] These threats would become more intense in a warming world (Ch. 2). Disruption of petroleum supplies has broader impacts on transportation, buildings, and industrial products.[80]

In 2020, Hurricane Laura disrupted more Gulf of Mexico crude oil production than any other storm since 2008.[81] Onshore processing facilities and power supplies were damaged, and industry response was limited by lack of resources, personnel, processing facilities, and power. Flooding from Hurricane Harvey in 2017 damaged large pipelines,[82] and excessive precipitation damaged floating-roof storage tanks.[83] Hurricane Ida in 2021 disrupted up to 95% of the Gulf Coast's crude oil and gas production.[84]

Extreme cold events in areas inexperienced with such temperatures are impacting oil and gas equipment and operations.[24] In regions where natural gas is used for heating and power generation, cold events are challenging because of increased demand combined with the risk of infrastructure failure.[85,86]

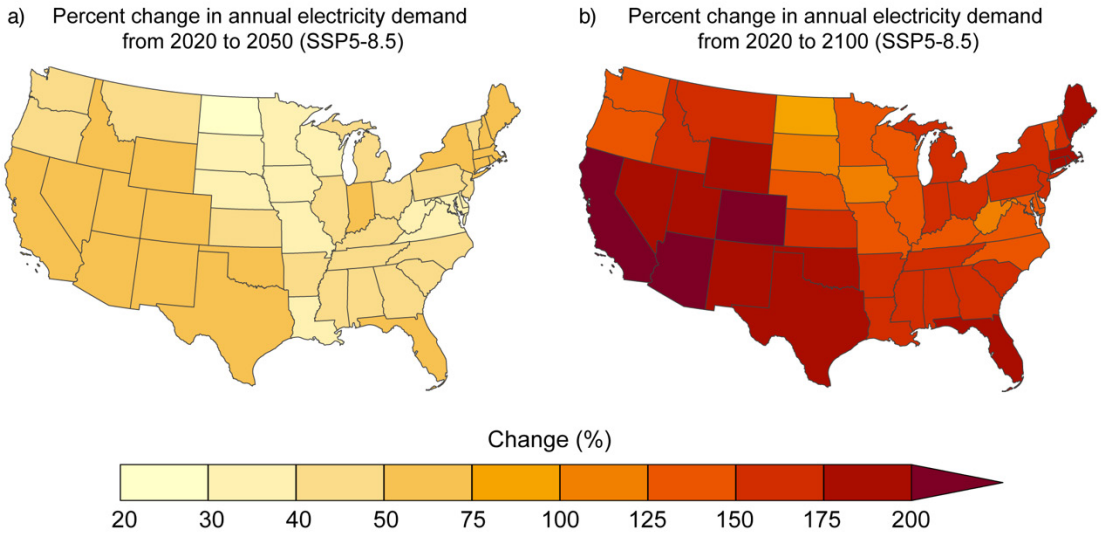
Although climate change often increases risks to energy production and delivery, warming temperatures have mixed effects on oil and gas production in cold regions. Warming benefits offshore production and shipping of petroleum products off the Alaska coast by decreasing sea ice and opening shipping routes. Average annual Arctic sea-ice extent during 2011–2020 reached its lowest level since at least 1850 (Ch. 2).[87] Ice-free summers are projected by 2050.[87,88] Warming temperatures in Alaska endanger inland oil and gas production and delivery as permafrost thawing compromises the structural integrity of wells, pipelines, storage tanks, railroads, and roads, impacting consumers and potentially contributing to methane leakage.[89] Fewer days for road travel on decreasing frozen tundra also has an impact on oil and gas exploration and production.[90,91]

## *Energy Demand*

Energy demand is projected to increase through 2050, driven by warming temperatures, increasing electrification, and economic growth.[3,92] Despite the increase, overall intensity of energy demand (energy consumed per household or per square foot of commercial floorspace) is expected to decrease.[3,92] Energy system modeling projects decreases in overall energy use relative to current levels if net-zero $CO_2$ emissions are achieved (KM 32.2).

Electricity demand is growing in many regions of the US, driven by population and economic growth; increased adoption of electric vehicles, heat pumps, and water heaters; and decarbonization goals, spurring additional electrification of transportation, industry, and buildings.[93] These trends also alter peak demand patterns.[94,95,96] Increased temperatures can further increase overall electricity demand, as illustrated in Figure 5.2.[97,98]

### Projected Changes in Electricity Demand




**Due to climate change, electricity demand is projected to increase over this century.**

**Figure 5.2.** Global change intersectoral modeling forecasts[97] that do not reflect the provisions of the Inflation Reduction Act project a potential increase in annual electricity demand of 25% to 70% from 2020 to 2050 (a) and 96% to over 215% from 2020 to 2100 (b) across much of the country, driven in part by increased ambient temperatures. Alaska, Hawai□i and US-Affiliated Pacific Islands, and the US Caribbean are not included due to the lack of high-resolution climate data informing those projections, but similar trends are expected. Increasing electricity demand is expected based on socioeconomic scenarios and adaptation approaches for the grid (KM 23.4). Changes are based on a very high scenario (SSP5-8.5). Figure credit: Pacific Northwest National Laboratory.

### Peak Power Demand

Temperature changes and extreme events alter peak power demands, driving the need for additional investment in energy infrastructure of 3%–22% by 2100.[99] Electricity needs for cooling buildings are projected to increase energy demands through 2050.[100,101,102] By 2050, warming summer temperatures are expected to increase residential electricity demand greatest in the South and Midwest, whereas warmer winter temperatures will reduce residential natural gas demand most in the South.[102,103] By the end of this century, the maximum summer cooling energy demand in the US could increase by 27% under a very high scenario (RCP8.5).[104]

Extreme events are expected to increase residential and commercial cooling demands,[100] placing additional stress on the power grid. Cooling demand in summer accounts for 30%–50% of the total daily electricity usage for the metropolitan areas of Sacramento, Los Angeles, and New York City. For every 1.8°F (1°C) of ambient temperature increase, daily electricity usage increases 6.2% in Sacramento, 4.7% in Los Angeles, and 5.1% in New York City.[105] During the 2021 heatwave in the Pacific Northwest, inland temperatures reached 120°F.[106] In Portland, Oregon, peak electricity demand was one-third higher in 2021 than in either of the prior two years.[107] Heatwaves will increase summer electricity demands if they lead to adoption and use of air-conditioning.[108]

### Oil and Gas Demand

Demand for oil and gas is projected to remain stable in the US through 2050, with technological advances including electrification and electric vehicles reducing potential consumption.[3] However, with high international demand for liquified natural gas, US production may rise, and the US will remain a net exporter of natural gas. Methane emissions associated with increased natural gas production will need to be addressed (Ch. 32).

## Key Message 5.2

## Compounding Factors Affect Energy-System and Community Vulnerabilities

Concurrent changes in technologies, policies, and markets, in addition to their interconnections, can reduce GHG emissions while also increasing vulnerabilities of energy systems and communities to climate change and extreme weather (*very likely*, *very high confidence*). Compound and cascading hazards related to energy systems and additional stressors, such as cyber and physical threats and pandemics, create risks for all but disproportionately affect overburdened communities (*very likely*, *very high confidence*).

### *Decarbonization*

Climate change is driving decarbonization efforts across the Nation, transforming the energy system through increased electrification and applications of wind and solar, hydrogen, bioenergy, modular nuclear, geothermal, hydropower, other long-term storage, and CCUS. Innovative energy market designs are being advanced to accelerate decarbonization. Under decarbonization scenarios that reduce economy-wide carbon emissions by at least 50% by 2030, electricity demand is expected to increase, led by transportation electrification. Demand increases vary across models from 2%–56% higher in 2030, compared to 2019 levels.[109] Projections of growing electricity demand in transportation vary from less than 10% to nearly 100% of sales by 2050,[95,96,110,111] depending on future regulations, incentives, and market acceptance. Additional electrification opportunities exist in buildings, including space and water heating, and in industry, including heat pumps and waste-heat recovery.[112,113] Replacing older air-conditioning equipment with heat pumps can improve energy efficiency for space cooling and heating, and demand-side management can reduce GHG emissions by shifting loads strategically in time.[114]

Clean hydrogen, produced with low-carbon energy, including renewable and nuclear, can help decarbonize transportation and industry (Ch. 32).[115,116,117,118,119] CCUS can reduce the carbon intensity of electricity production and combustion in industry and can be paired with bioenergy to yield additional carbon reductions.[120,121]

Rapid deployment of decarbonization technologies will create additional challenges (KM 32.2).[122,123,124] For example, vehicle electrification requires expansion of electric vehicle and battery manufacturing capacity, development of charging infrastructure, expansion of transmission, adaptation of refining operations to reflect lower demand for gasoline and diesel, and emergence of industries for recycling, repurposing, or disposing of end-of-life batteries (KM 13.4).[125,126] Vulnerabilities to climate change may increase with decarbonization; for example, a greater reliance on electricity and bioenergy could exacerbate the impacts of power outages and droughts.[85,127]

Consumer behaviors and social norms influence the adoption and actual performance of decarbonization technologies, such as home energy management systems and rooftop solar.[128,129,130,131] More efficient technologies can decrease costs to consumers, increasing activities such as driving and space heating.[132]

## Resource Constraints

Global disruptions, such as the COVID-19 pandemic,[133,134] cause shortages of materials and available workforce, limiting the transition to energy system decarbonization. Some energy technology supply chains, particularly solar PV and electric vehicle batteries, are more susceptible than others to resource constraints (KM 13.4).[135,136] Island communities are especially vulnerable and slow to recover when supply chains are severed by extreme events (Ch. 23).[137]

Critical materials, such as rare-earth minerals used in batteries and electric motors, are predominantly extracted and produced outside the US (Figure 17.2; Ch. 32). Geopolitical and environmental factors influence how these materials are extracted, used, and recycled (Focus on Risks to Supply Chains).[138] Securing reliable, environmentally sustainable domestic sources of critical minerals is a national priority given the growing demand for low-carbon energy technologies.[139]

Energy system expansion to meet future demands requires suitable land, which may be limited by climate change.[140] As demand for new generation and transmission grows, integrated land-use strategies are emerging to support multiple objectives, including increases in food security, local manufacturing, and energy system resilience, as well as land and water conservation. Examples include combining solar energy with agriculture or mounting solar panels on floating structures.

## Vulnerable Communities and Equity

Overburdened communities are disproportionately affected by climate impacts and energy injustice. These populations suffer more from power outages,[141] high energy prices, and health concerns from pollutants and wastes produced by fossil fuel power plants and refineries.[142,143,144,145] After Hurricane Ida (2021), areas with high proportions of Black residents had longer waiting times for power to be restored.[61] Indoor $CO_2$ levels associated with fossil fuel combustion have been linked to reduced human cognition (Ch. 15).[146] Overburdened communities may benefit most from decarbonization and increased energy system resilience.[147,148,149,150,151]

Extreme heat disproportionately impacts overburdened communities,[149,152] especially in urban locations where asphalt is plentiful and trees are rare.[108,153] Lower-income households that do not have or use air-conditioning are at higher health risk, such as witnessed during the unprecedented heatwaves in the Pacific Northwest (Ch. 15).[108,154]

Communities without access to reliable power are more susceptible to hazards from extreme weather events. Following Hurricanes Irma and Maria (2017), rural areas in Puerto Rico and Florida had longer power outages and slower restoration times.[141,155,156] A lack of adequate insulation accentuated effects of the 2021 winter storm in Texas on Black communities of low socioeconomic status.[157] Power outages can increase

injuries and deaths from carbon monoxide poisoning through use of gasoline-powered generators, charcoal grills, and kerosene and propane heaters inside homes lacking proper ventilation.[158,159]

Energy burden (energy cost as a percentage of household income) is an indicator of community and household vulnerability.[143,160,161,162] Nationally, rural low-income households experience the highest median energy burden at 9% (with some regions as high as 15%), compared to 3% for rural middle- and high-income households and compared to lower values for metropolitan households.[163]

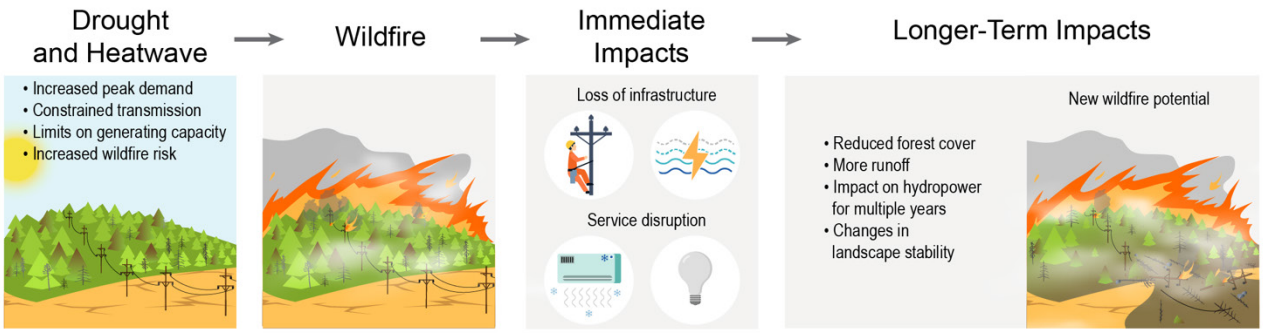
Energy inequities can be associated with lower-carbon energy sources. While the energy transition will create new economic opportunities, communities and individuals relying on employment and tax revenues from coal, oil, or natural gas can become more economically vulnerable. Individuals who held fossil fuel jobs may have difficulty finding a new job because of skills gaps, wage loss, long-distance commutes, or the need to relocate.[164,165] The number of solar and wind energy construction jobs in former coal communities may not be sufficient to replace the supply of former coal jobs.[166] Reuse of existing fossil fuel infrastructure to transition to clean energy sources may allow economically vulnerable communities to transition in place.[167] Employment and wage losses in fossil fuel sectors could be offset by increases in low-carbon resource industries,[168,169,170] although counties in Appalachia, the Gulf Coast region, and the intermountain West are expected to experience the most significant impacts, including to local services, as the tax base diminishes.[105,171,172]

## *Compound and Cascading Hazards*

Climate change poses acute and chronic hazards to the energy system and communities from coinciding or sequential trends and extreme events (Figure 5.3; Ch. 18). Climate projections for 2041–2050 show increased power demand in Texas at the same time power supply may decrease, due in part to potential decreases in renewable resources such as wind, as well as reductions in output power from thermoelectric power plants due to warmer ambient temperatures.[173] Sequential events can compound impacts if recovery has not occurred before the next event or hazard.[174,175] Vulnerable communities near Houston, Texas, were adversely affected by the 2021 winter storm before they had recovered from Hurricane Harvey in 2017.[157] Some areas may be more vulnerable to compound hazards; for example, urbanization exacerbates or combines with flooding to compound effects on coastal infrastructure.[176]

Cyber and physical risks can add to the vulnerability of the power grid to climate change and extreme weather, especially if these events coincide.[177,178] Cyber and physical attacks are sometimes intended to compound damage to the power grid caused by extreme events.[179] Multidirectional flows of data, fuels, and electricity increase vulnerabilities. Furthermore, increased renewable energy penetration and distributed energy systems (technologies that generate electricity at or near point of use) are new variables affecting risk of power outages during extreme events.[177,178] New methods are available to assess power system vulnerability to these stressors and to quantify resilience.[180]

### Consecutive and Cascading Events Involving the Energy System




**Sequential and concurrent climate impacts have near-term and long-term effects on electricity generation and distribution.**

**Figure 5.3.** Drought and heatwaves can reduce electricity generation and delivery through cascading mechanisms. Droughts reduce water availability and electricity generation. Stressed vegetation, including tree mortality following insect outbreaks, fuels wildfires. Concurrently, heatwaves increase electricity demand and reliance on transmission, which can also trigger wildfires. Wildfires damage electricity infrastructure, disrupting power and associated services. Reduced vegetation increases runoff, resulting in floods and landslides and increased risk of wildfires. The cycle of events can accelerate, as new vegetation is more sensitive to droughts and heatwaves. Figure credit: Oak Ridge National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory.

Cascading hazards can cause additional burdens to the energy system. For example, intense rains over areas burned by wildfire are projected to increase in California, intensifying flooding challenges for energy infrastructure.[181] Summer cooling demand resulting from warmer temperatures sometimes coincides with reduced hydropower due to alterations in timing of peak streamflow.[182] Additionally, flooding followed by high temperatures that increase cooling demands can overwhelm the power grid.[183]

During the 2021 winter storm in Texas, extreme low temperatures caused high demand for electricity and fuels, equipment failures in fossil and renewable generation, and supply chain disruptions (Box 26.2).[24,85] Natural gas wells and gathering lines froze, compressor stations experienced power outages, and power plant equipment malfunctioned.[24] Disruptions to power supply and delivery triggered cascading failures in other critical sectors, including municipal water supply and medical services.[24,184] At least 210 deaths resulted from the outages and cold weather.[185]

## Key Message 5.3

## Efforts to Enhance Energy System Resilience Are Underway

Federal, state, local, Tribal, and private-sector investments are being made to increase the resilience of the energy system to climate-related stressors, and opportunities exist to build upon this progress (*very high confidence*). Ongoing investments will need to include improvements in energy-efficient buildings; technology to decarbonize the energy system; advanced automation and communication and artificial intelligence technologies to optimize operations; climate modeling and planning methodologies under uncertainties; and efforts to increase equitable access to clean energy (*very high confidence*). An energy system transition emphasizing decarbonization and electrification would require efforts in new generation, transmission, distribution, and fuel delivery (*very high confidence*).

Activities to increase energy system resilience include upgraded grid design, hardening of energy infrastructure, vegetation management to reduce wildfire[186,187] and trees falling on powerlines,[188] and clean energy microgrids for communities vulnerable to power outages.[189] Battery storage combined with solar PV can improve building resilience during power outages.[190] Strengthening natural gas pipelines, as well as conducting periodic stress evaluation and maintenance, reduces risk from subsidence.[69] Options for oil production include providing heated water systems at drill sites to prevent freezing and upgrading platform rigs to be resilient to hurricanes.[191] Multiple opportunities are available for climate risk management in the electric utility industry,[192,193,194] with some states (e.g., California, Oregon, and New York) requiring electric utilities to conduct climate vulnerability assessments (KMs 21.4, 32.5).

## Improved Climate Modeling to Inform Planning for Energy System Resilience

Improved accuracy, detail, and modeling capabilities are allowing high-resolution Earth system models and human–Earth system models to help decision-makers reduce vulnerabilities to climate change and inform energy system plans and operational strategies across spatial scales.[14,45,195,196,197,198] For example, identifying where storm surge may threaten energy infrastructure could lead to fortifying or moving that infrastructure.[199] Projections of the severity and duration of future droughts could guide decisions to reduce water demand for energy supply.[200,201]

Modeling advances are improving understanding of climate impacts and wildfires on transmission lines[165,202] and solar PV,[21] stream temperature for thermoelectric power plants,[52] and water availability for the production of hydropower[45] and hydrogen.[203] Model applications include estimating lost power and restoration costs from hurricane damage.[204] Studies have investigated integration of climate-related impacts into long-term planning to achieve resilience to future extreme events.[39,205,206,207,208]

Efforts are underway to understand the range of climate impacts on interconnected energy systems, including improvements to multisector models,[209,210] observations[48] and analytics,[182,211,212] and development of Earth system models with advanced climate–human feedbacks.[213] Analyses of extreme events such as the 2021 extreme cold event in Texas,[85] the cascading power outages in California in 2020, and Hurricane Maria in Puerto Rico in 2017[214] can be used to plan and design for cross-sector resilience.

## Addressing Compound Threats

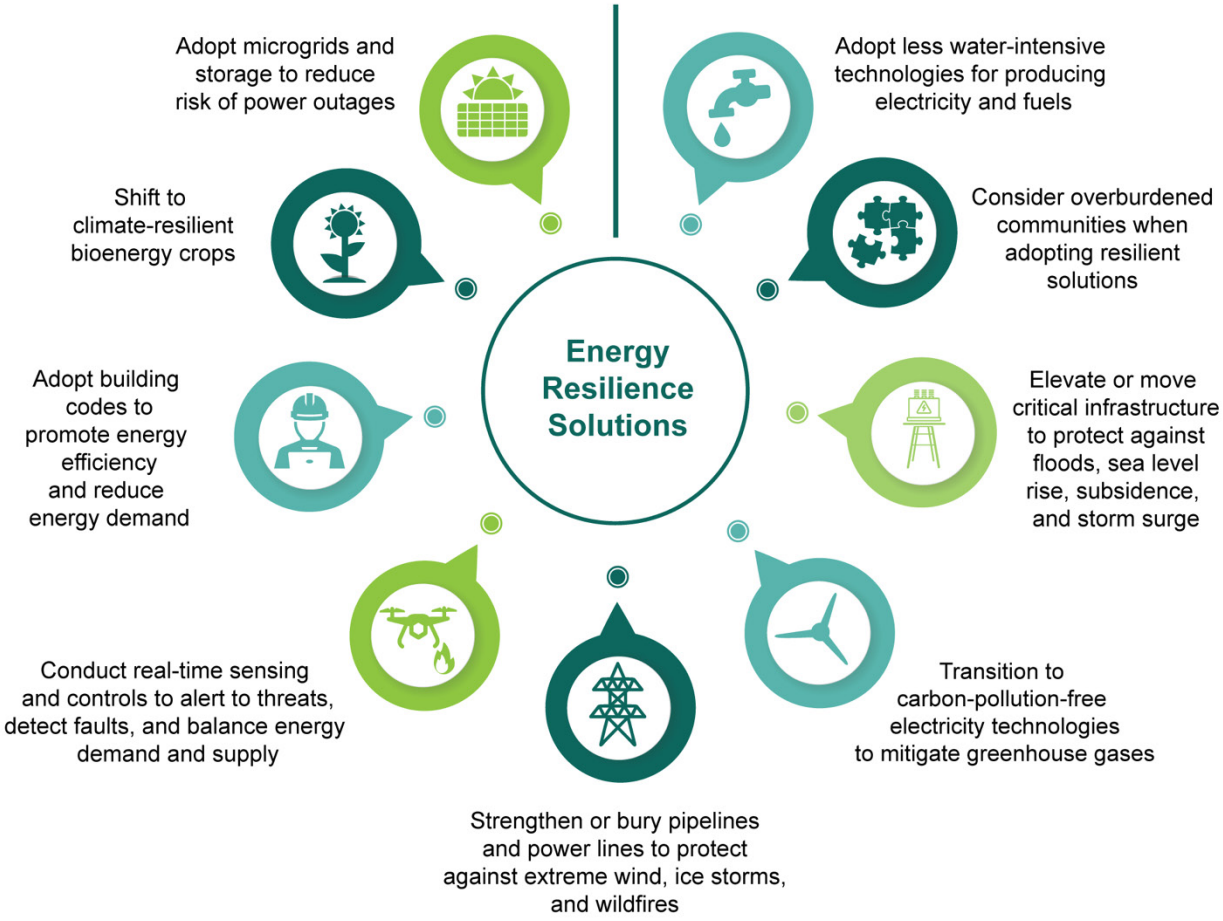
Progress is underway to develop and implement solutions addressing energy system risks from compounding impacts of climate change and threats from pandemics (COVID-19), cyberattacks,[177,215,216] electromagnetic pulse events,[85,174,176,180,217] market shocks,[218] and supply chain disruptions (KM 5.2). Examples include holistic modeling and analyses that reflect the interconnectedness of energy and water systems and the design and operation of energy systems that account for combined effects of climate trends and extreme weather events.[205,219]

## Hardening Energy Systems to Reduce Vulnerabilities to Climate Change

Energy system design and operations are being hardened to reduce vulnerabilities to climate change (Figure 5.4). Examples include elevating or moving equipment to avoid floods, strengthening pipelines and powerlines or moving them underground to reduce wind or ice damage and risk from wildfire, and recycling cooling water and deploying dry cooling technologies to reduce power plant susceptibility to drought.[220] Improving building codes can bring changes (e.g., grid-interactive efficient buildings, cool roofs, resilient construction materials) to the built environment (Ch. 12), enabling energy and emissions reductions (Ch. 32) and technologies (e.g., adaptive buildings, PV-ready buildings; Ch. 31) to advance resilience to climate change. Drones and sensors identify wildfire risks in real time, allowing protective actions to be taken.[221]

New tools and models are available for identifying infrastructure vulnerabilities and storm probabilities and for identifying effective hardening approaches,[214,222,223] including accelerated infrastructure investments to improve resilience of coastal systems to storm events.[224]

## Potential Energy System Resilience Solutions




**Many strategies are available to increase energy system resilience to climate change.**

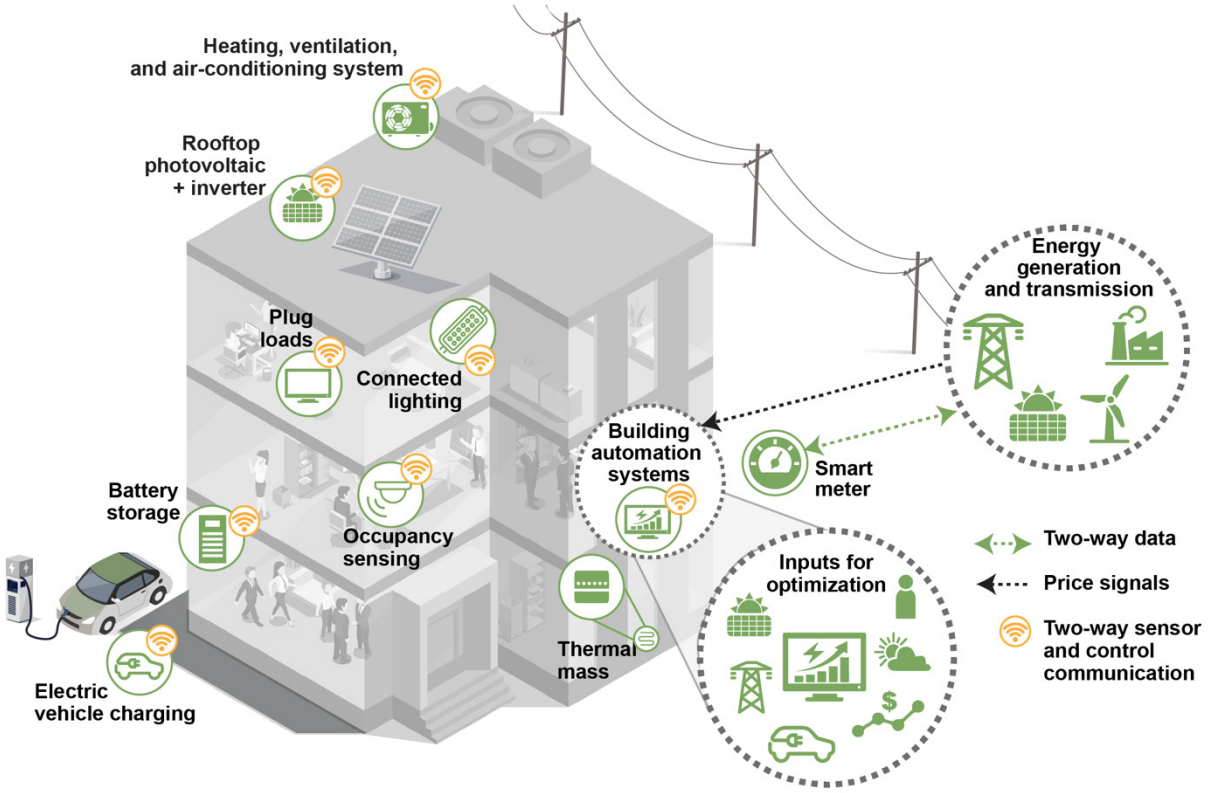
**Figure 5.4.** While climate change results in risks to the energy system, many approaches for enhancing energy system resilience are available. Resilience options include burying powerlines, elevating critical infrastructure, Introducing microgrids and distributed generation, and improved monitoring. Figure credit: EPA, FEMA, and DOE.

## *Automation, Information Technologies, and Grid-Interactive Efficient Buildings*

Advances in sensing, smart metering, and internet-connected appliances have enabled real-time monitoring of energy systems. Machine-learning algorithms are facilitating insights into energy supply, demand, and operations.[225] The electric grid can be more resilient to climate stressors if future renewable energy generation is better forecasted, operational faults are detected and diagnosed, supply and demand are balanced to account for variable generation and vehicle charging, and cyberattacks are detected.[226]

Grid-interactive efficient buildings (Figure 5.5) apply energy efficiency, smart technologies, and flexible load management.[227] Advanced control systems[228,229] predict energy demand in real time and maximize efficiency, minimize cost, and lower carbon emissions of HVAC systems. Application of natural gas demand response to residential heating during extreme cold conditions is projected to reduce demand by up to 29%.[86] By reducing and shifting the timing of electricity consumption, grid-interactive efficient buildings could decrease carbon emissions by 80 million metric tons per year by 2030, or 6% of total power sector carbon emissions.[227]

### Grid-Interactive Efficient Buildings




**A reimagination of building design and operation is being driven by decarbonization goals.**

**Figure 5.5.** Grid-interactive efficient buildings (GEBs) integrate energy efficiency technologies (HVAC, plug loads, lighting), on-site renewable energy (photovoltaics), electric vehicles, and electric storage with smart sensing (HVAC, lighting, and occupancy) and control optimization to enable demand flexibility and provide excess electricity to the power grid through the smart meter when demand exceeds supply or when supply from the grid is constrained. The building automation systems can import the grid electricity pricing and carbon-intensity factor in real time and communicate the potential to reduce demand to the grid through the two-way sensor and communication protocol. Adapted from Nubbe and Yamada 2019,[230] © 2019 Guidehouse Inc.

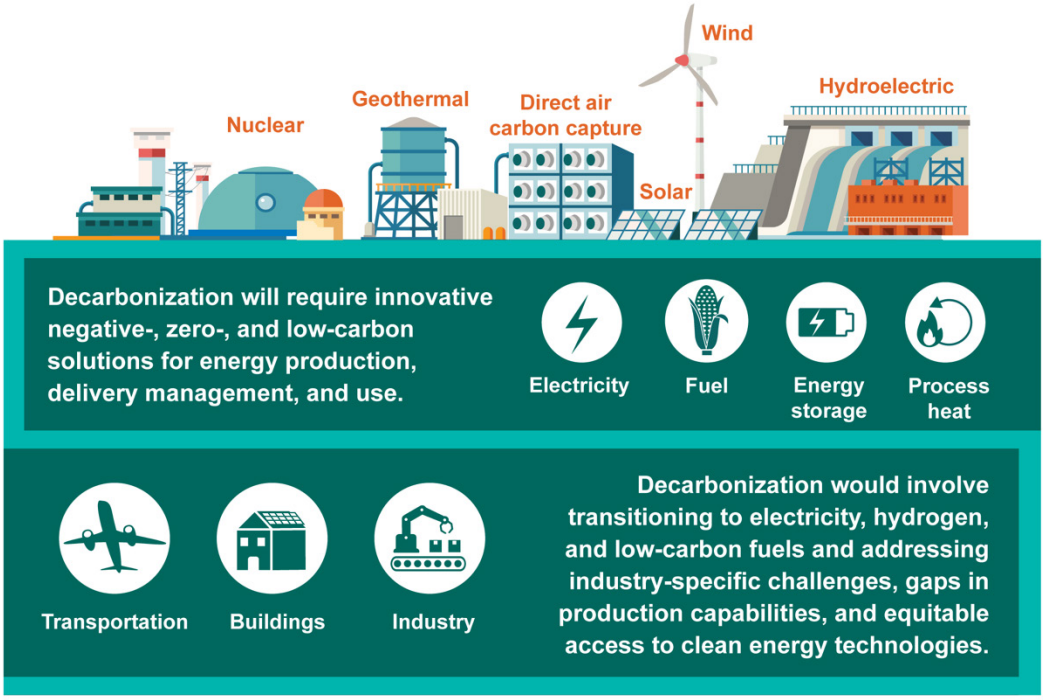
## *Technology Development and Deployment to Decarbonize the Energy System*

A major transition is underway to decarbonize major economic sectors (Figure 5.6),[231,232,233] supported by policies (e.g., mandates to reduce fossil fuel use, tax incentives), falling costs, and technology innovations. Significant advancements in low-carbon energy technologies have been made in the electricity sector.

Growth in electric power demand is projected due to increasing electrification and ongoing economic growth. Declining capital costs and government subsidies, including IRA initiatives, are projected to drive increasing renewable energy generation from solar and wind by about 325% and 138% respectively, by 2050 as compared to 2022.[3] Increased electrification of end-use sectors is projected with the adoption of more heat pumps and electric vehicles, as well as electric arc furnaces in the iron and steel industry.

Some technologies can provide energy benefits to other sectors. For example, nuclear power produces thermal energy that can be used in industrial applications, substituting for fossil fuels. In addition to reducing energy-related emissions, electricity may be more reliable, efficient, and economical compared to other energy sources.[95] High electrification rates could be supported by greater integration of renewables.[93,234]

### Energy System Decarbonization

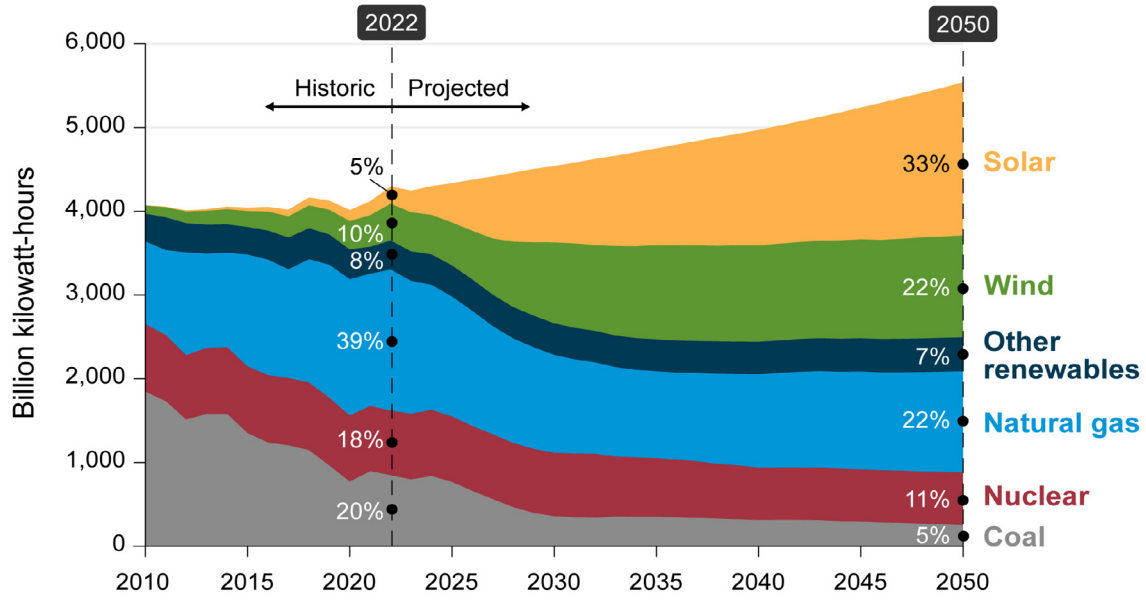



**Decarbonization will require innovative solutions across multiple sectors.**

**Figure 5.6.** Energy system decarbonization will rely on increased innovation, deployment of clean energy technologies including carbon capture, small modular nuclear reactors, hydrogen, and further integration and electrification of residential and commercial buildings, industry, and transportation. Figure credit: DOE, Idaho National Laboratory, NOAA NCEI, and CISESS NC.

With wind and solar costs dropping 70% and 90%, respectively, over the last decade, capacity additions are reaching historic levels[235] and are projected to increase (Figure 5.7).[3,112,236] Advances contributing to cost reduction include technological advances, improved efficiency in energy generation and manufacturing, reduced capital costs, and accumulation of operational experience. However, greater transformation is needed to meet goals of 100% clean electricity in 2035 and net-zero GHG emissions by 2050.[237] Meeting both goals requires electrification of transportation, buildings, and industry and production of low-carbon electricity from renewable, nuclear, and fossil fuel energy with carbon capture.[112,123,238] The rate of decarbonization will be determined, in part, by public acceptance of new energy technologies and infrastructure.[239]

## Historic and Projected US Electricity Generation Sources




**The Nation's electricity grid continues to expand use of clean energy technologies.**

**Figure 5.7.** Most electricity generation projections see significant growth for renewable sources. Recently enacted legislation is anticipated to increase deployment rates for low-carbon technology. Adapted from EIA 2023.[3]

Advances are being made in performance and cost for other energy technologies. Over the last decade, costs of lithium-ion batteries for electric vehicles have dropped 85%,[240] and progress is being made to recycle batteries and develop alternative materials beyond lithium. Efforts to lower production costs for clean hydrogen by 80% to $1 per kilogram could unlock new markets and create jobs in industries such as steel manufacturing, clean ammonia production, energy storage, and heavy-duty trucks.[241]

Demonstrations for advanced small modular nuclear reactors have begun with design approval from the US Nuclear Regulatory Commission,[242] as well as efforts to use existing nuclear power plants and fossil-fueled power plants with carbon capture to generate clean hydrogen and purify water in addition to producing electricity.

## *Solutions for Vulnerable Communities and Energy Justice*

Policies related to energy system decarbonization can promote energy equity. Procedural justice, which relates to equitable participation in and influence on energy decisions,[243] is key to equitable energy solutions. Opportunities to promote energy equity and reduce energy burdens include collective, inclusive decision-making around utility-initiated power shutdowns; adopting energy storage with decentralized solutions, such as microgrids or off-grid systems;[73] developing community-sharing opportunities for solar energy (including rooftop solar) and energy storage;[144,244] and building emergency cooling or heating shelters to serve overburdened communities.[245] An example of a Tribal community addressing a just transition from fossil fuels to renewable energy is the Blue Lake Rancheria Tribe's large-scale solar and microgrid project.[223,246]

Many decarbonization technologies are expected to decrease environmental impacts such as air pollution (KMs 14.5, 32.4),[247,248,249,250] potentially benefitting overburdened communities that disproportionately experience pollution from roadways, refineries, and power plants.[251,252,253] However, impacts of some decarbonization technologies can shift the magnitude, location, and type of pollution (KM 32.4).[254,255,256,257] Environmental regulations and permitting requirements play an important role in addressing impacts.

Energy burden remains high for overburdened groups. Many policies and programs that promote clean energy or energy efficiency are inaccessible to low-income households.[258] Policies that fix energy prices during extreme events or prioritize energy restoration for overburdened communities can provide more equitable support.[184] Federal assistance programs can help communities overcome climate challenges and enhance resilience (Ch. 31).[259] In addition, federal programs are being established to promote energy equity and serve overburdened communities.[260,261]

# Traceable Accounts

## *Process Description*

The author team was selected to bring diverse experience, expertise, and perspectives to the chapter. Some members have participated in past Assessment processes. The team's diversity appropriately reflects the spectrum of current and projected climate impacts on the Nation's complex energy system, the energy system's roles in national security and economic well-being, and the need for equitable access to reliable and affordable energy and environmental justice. The all-federal composition of the author team was a decision of the National Climate Assessment (NCA) Federal Steering Committee. The author team has demonstrated experience in the following areas:

- characterizing baseline supply and demand for electricity and fuel from diverse sources at multiple scales;
- characterizing effects of climate on the energy sector—as well as opportunities for climate change mitigation and options for increasing resilience to climate-related stressors—at national, regional, state, and local levels;
- developing and implementing energy system models for projecting technology deployment, fuel use, and greenhouse gas (GHG) and air pollutant emissions over wide-ranging scenarios;
- analyzing energy system sensitivities to drivers such as policy, markets, technology, and physical changes;
- developing and implementing climate science models, tools, and information for characterizing energy sector risks;
- supporting local, state, Tribal, federal, and private-sector stakeholders in integrating climate change issues into long-range planning and project implementation;
- assessing the environmental impacts of new and emerging energy technologies; and
- analyzing technological, societal (including justice), economic, and business factors relevant to risk reduction and energy system resilience.

The author team met virtually on a weekly basis to develop the chapter, address issues, and build consensus. In addition, the team met with representative authors from other chapters to identify and address cross-cutting issues. To ensure the chapter is informed by and useful to stakeholders, a public engagement workshop was held to provide participants an opportunity to exchange ideas with the author teams on chapter key topics, share resources, and give feedback on issues of importance to them. Participants in the workshop represented government (federal, state, local, and Tribal), nonprofits, academic institutions, businesses and the private sector, community groups, students, and others.

To develop Key Messages, the team conducted searches of the scientific literature, including peer-reviewed journal articles, government reports, and reports of nongovernmental organizations, as well as incorporating input from the workshop. The team drew on measurements (e.g., data on ongoing effects of past extreme events and government energy data); model outputs (e.g., from climate models, models of energy supply and demand, models of climate effects, and models of resilience of climate change stressors on the energy system); published perspectives of experts, some of which identified sources of uncertainty; and input from the workshop and from peer reviewers of this chapter. The chapter does not reference newspaper articles.

## Key Message 5.1

# Climate Change Threatens Energy Systems

### Description of Evidence Base

The impact of increased concentrations of greenhouse gases (GHGs) on global warming (Ch. 2) and sea level rise (Ch. 3) is well established in the peer-reviewed research and supporting publications, and the impact of climate change on extreme events is growing (Ch. 3). Mechanisms by which climate change impacts energy infrastructure and electricity demand also have a strong research foundation, with extensive documented analyses of climate trends and past extreme events, as well as peer-reviewed research on projected impacts that uses empirical data[262] or downscaled climate projection data[29,263] and detailed models of possible future energy system designs.[264] One new study linked the output of global climate models to a weather forecasting model to project regional energy effects.[32] The importance of extreme events has required new types of empirical models, some of which are integrated with climate models or outputs (e.g., the relationship between smoke and photovoltaic capacity or productivity).[21,22] Historical data on hurricanes are combined with ocean models to better understand variables important to offshore wind energy.[13] New econometric models based on weather variables, consumption data, and population growth estimates are also important components of the evidence base related to electricity demand projections.[103] There is strong agreement in the literature on mechanisms and types of electricity demand impacts,[265] although impacts are expected to differ by location.[103] The magnitudes of projected energy system impacts are dependent on the magnitude of climate change and the increased rate, magnitude, and location of extreme events (KMs 23.4, 27.4). There is a foundation of regional-level studies on how the energy system is being impacted and is projected to be impacted[31,32] and, ultimately, how those impacts may affect energy users locally. Where and when these impacts will occur locally is much harder to model in the context of temperature and precipitation trends and especially in the context of extreme events than at the more regional and continental scales.[8]

### Major Uncertainties and Research Gaps

Much of the key evidence related to extreme events is empirical and opportunistic. Although significant data are available to document the effects of extreme events on energy systems, those data and analyses are typically published two to four years after the event. For example, at the time this report was written, important papers were still being published on infrastructure and energy justice effects of Hurricanes Harvey, Irma, and Maria in 2017.[82,141,155,157] Most analyses of the impacts of Hurricane Ida in 2021 will not be available for several years, although Coleman et al. (2023)[61] is an exception. Opportunities exist for more timely assessments of major impacts of extreme events on energy systems to inform relevant policy discussions, investments, and efforts to increase energy system resilience and human adaptation.

There is more confidence in national projections of climate variables and extreme events than in estimates of local impacts. Therefore, the authors are confident that the frequency and intensity of extreme events will increase nationally (Ch. 2) but not as confident in the locations of specific events that may impact energy supply and demand over the coming decades.[13,266] Similarly, projections of wind power are only as good as the often-coarse spatial and temporal resolution of the climate models used.[31] The authors are confident that the demand for cooling buildings in summer will increase in most regions across the continental United States.[103] In studies where climate projections are downscaled, computational demands and data storage requirements limit the number of projections that can be used and therefore increase uncertainty, as recognized by cited authors.[263] Cost projections for physical damages to infrastructure do not include those from floods, high winds, and ice storms, which are poorly represented at the coarse spatial scale of climate models.[57]

Furthermore, in the studies cited, there is sometimes disagreement among researchers. Whereas emerging research suggests that the frequency of cold-weather events and heavy snowfall may be increasing because

of warming Arctic temperature,[267] there is some disagreement in the research community[268,269] regarding this projection and the impact such a change may have on increasing or decreasing future heating demands regionally. Furthermore, there is uncertainty regarding future wind resources and trends.[31,262,270]

Many model inputs are uncertain. For example, potential bioenergy projections are dependent on uncertain $CO_2$ fertilization intensity.[30] Furthermore, projections of electricity and natural gas demand are sensitive to socioeconomic factors, such as the ratio of urban to rural population or changes in energy prices that may reflect the pace of shifts in energy technologies.[103]

### Description of Confidence and Likelihood

Based on historical data, recent trends, modeling projections, and attribution analytics, there is *very high confidence* and it is *virtually certain* that climate change and extreme weather are negatively impacting the Nation's energy system and that, unless action is taken, climate change will continue to affect the energy system, including damaging energy infrastructure and operations. There is *very high confidence* that energy supply and delivery are at high risk from climate-driven changes,[271,272] including shifts in demand,[45,273] damage to infrastructure and operations,[271,274] and resulting effects on human lives and livelihoods. It is *virtually certain*, based on past experience and modeling projections, that climate change trends will continue (Ch. 2), and effects on energy systems will vary over time and location and increase with projected increases in the frequency, intensity, and duration of extreme weather threats, including extreme precipitation, extreme temperatures, sea level rise, and more intense storms, droughts, wildfires, and thawing of permafrost.

## Key Message 5.2

## Compounding Factors Affect Energy-System and Community Vulnerabilities

### Description of Evidence Base

#### Decarbonization

There is growing evidence from peer-reviewed analysis demonstrating both the need for and progress in decarbonization of the energy system through increased electrification and applications of clean energy, including wind and solar; hydrogen, bioenergy; modular nuclear; geothermal; hydropower; other long-term storage; and carbon capture, utilization, and storage (Ch. 32).[95,96,109,110,111,112,113,114,115,117,118,119,121] However, additional studies are needed to better characterize how the rapid deployment of decarbonization technologies will create additional compounding challenges (KM 32.2),[122,123,124] including the need for additional energy infrastructure associated with expansion of electrification demand (including generation, transmission, and distribution), expansion of electric vehicle and battery manufacturing capacity, development of charging infrastructure, adaptation of refining operations to reflect lower demand for gasoline and diesel, and emergence of industries for recycling, repurposing, or disposing of end-of-life batteries (KM 13.4).[125,126] More information is also needed to better characterize consumer behaviors and the cost and performance of decarbonization technologies, which will influence the pace, scale and scope of their adoption by society.[128,129,130,131,132] Opportunities exist for better characterizing the co-benefits of both reducing GHG emissions and increasing climate resilience through decarbonization, including, for example, quantifying the benefits of deployment of distributed clean energy generation with microgrids and storage that reduces emissions and provides backup generation during power outages.

#### Resource Constraints

Whereas there is abundant research and industry knowledge on global supply chain dynamics, commodity markets, and strategic materials, there is less peer-reviewed literature focusing specifically on the current

and anticipated future supply chain and resource constraints associated with those parts of the energy system that are gaining, or anticipated to gain, greater market share in the energy economy, including electric vehicles, wind and solar energy, and battery storage. Research is lacking in this area, including on the relationships and sensitivities across parts of the energy sector that may be competing for the same source materials, as well as on the potential for alternative materials or processes that may help address supply chain constraints or risks, particularly where sectors other than energy may be competing for similar feedstocks, materials, or personnel.

### Cyber and Physical Threats to the Power Grid

A growing body of peer-reviewed research related to cyber/physical security argues for the joint consideration of climate change and cyber/physical attacks in grid analyses and resilience responses.[177,178] However, many data-driven analyses of actual system incidents, response measures, and defenses are not publicly available and therefore are not referenced. There is growing research on human and environmental threats to the power system, how they relate to each other, and how multiple objectives like decarbonization of the energy system, system resilience to climate stressors, and cyber defenses can be optimized as the energy generation mix changes and threats evolve across the grid and other energy infrastructure.[177,178]

As with cybersecurity, a significant amount of non-peer-reviewed analysis related to compound and cascading hazards and threats is occurring in the classified domain, particularly in those cases that involve a human threat or cyber incident. Furthermore, anecdotal news reports refer to consecutive extreme events, but insufficient peer-reviewed evidence is available to indicate whether some of these compound threats are increasing, that there is a causal association between them, or that they have a compounded effect on energy systems. In addition, while information is available on characterizing the benefits of a smart grid system that can automatically reroute power to electrical systems that are most needed to minimize impacts of outages, opportunities exist to better characterize the unintended consequences of a smart grid system and its increased susceptibility to extreme weather and cyber threats.

### Vulnerable Communities and Equity

An abundance of peer-reviewed research on environmental justice relates to the placement of fossil fuel power sources and resultant air pollution[145] and health threats in or near overburdened communities. A growing body of evidence shows that overburdened communities are disproportionately affected by the impacts of climate change, including resource-constrained abilities to migrate and low access to high-quality infrastructure such as air-conditioning.[275] Furthermore, inequitable exposure to heat islands in cities is addressed by analysis in the peer-reviewed literature.[149,152] More information is available on inequities in electricity delivery (e.g., energy access, energy burden,[162] and electricity restoration times[61] than on inequities in supply or on differential demand (including cooling-system-use temperatures[154]) in response to climate change and extreme events.

### Compound and Cascading Hazards

There is a growing body of peer-reviewed research focused on understanding climate, ecosystems, and human systems and implications for the energy system. Notably, significant progress has been made over the last decade to better understand the agriculture–energy–water nexus, correlated risks in these three domains, and strategies to address them. Multiple extreme events and other climate-related stressors are affecting the same regions; for example, wildfire may be followed by floods,[181] and multiple hurricanes may affect a single coastal location.[157] Climate projections show that increased demand and decreased supply of electricity will coincide in regions during heatwaves.[173] Recent extreme heat (e.g., Turner et al. 2021[55]), extreme cold (e.g., Busby et al. 2021[24]), and flooding (e.g., Collins et al. 2019[147]) events in Texas, for example, have helped advance a growing body of research to understand the relationships between the electric grid, fuel supply and infrastructure, and market design and pricing, as well as how humans respond to real-time

extreme events and how overburdened communities are disproportionately impacted.[157] These are complex, dynamic systems. While emerging multidisciplinary modeling frameworks are improving the understanding of dynamics of multisectoral systems that include energy, many opportunities exist for improving these frameworks, including improving spatial and temporal resolution, sectoral detail, cross-sector interactions, representation of factors impacting energy and environmental justice, and utilization of high-performance computing to address data and computational requirements.[174,176]

## Major Uncertainties and Research Gaps

Increased multidisciplinary and cross-sectoral analysis and research can lead to an improved understanding of the compound and cascading hazards across the energy system. Because cascading threats are correlated, they may be easier to predict than compound threats, which are independent.[176] Data-driven analysis could be undertaken to inform the understanding of complex-system dynamics impacting climate risks and vulnerabilities in the energy sector that involve human behavior, markets, infrastructure, electricity, fuels, and environmental conditions.

Energy justice research results are sensitive to spatial scales of analysis.[239]

The limited sample size of localities, regions, or sectors that have achieved their decarbonization or electrification goals to date limits information that can inform analyses of climate implications for the energy system. The majority of peer-reviewed research does not address past or current efforts but rather is forward-looking, addressing potential implications and opportunities. There is a pressing need for greater insights on the near-term localized impacts of decarbonization efforts on aging distribution networks, particularly where electric vehicle penetration is growing rapidly.

Research gaps include the need to better understand global supply chain implications and relationships across those technologies or materials that will be important for mitigating climate change and increasing resilience of energy systems to climate-related stressors and events. There is also a need to better understand other resource constraints informing rapid scaling of decarbonization strategies, such as land-use optimization and trade-offs, infrastructure constraints, human dimensions of energy transitions including workforce development, and pathways for developing and using alternative feedstocks or materials, particularly those that may mitigate geopolitical or security risk. There is uncertainty regarding how cascading events will change in the future, how human activities will alter the risk of compound events, and how new infrastructure design guidelines might alter risk.[174]

Cross-fertilization of research between utilities and industry, classified domain research, and public peer-reviewed research could help researchers better understand current and future cyberthreats to the energy system, including how and where those threats may exacerbate or exploit climate change–related risks.

## Description of Confidence and Likelihood

Based on a growing body of evidence, including recent trends and peer-reviewed research, there is *very high confidence* that compound and cascading hazards—many of them climate related[175,179,181]—and compounding effects of changes in technologies, policies, and markets will continue to impact the climate change vulnerability of the Nation's energy system. It is *very likely* that energy system decarbonization and increased electrification will create new and growing demands on existing electricity infrastructure and will require significant investment in new generation and delivery.[124] While these changes will reduce dependency on fossil fuel sources, it is *very likely* that, unless addressed, they will result in increased vulnerabilities and supply chain constraints.

## Key Message 5.3

# Efforts to Enhance Energy System Resilience Are Underway

### Description of Evidence Base

Much of the evidence for this key message is qualitative, with citations in the main text. For example, energy resilience options and decarbonization technologies are described in the main text with no additional evidence here.

Evidence that efforts for energy systems are underway include legislation and states' recommendations. Overall, the energy sector is leading the way on decarbonization of the economy, with 22 states, the District of Columbia, and Puerto Rico having enacted legislation to reach 100% clean energy goals.[276] Integrated resources plans (IRPs) are required from electric utilities in 33 states that work with partners on the development of adaptation framework specific to the electric utility sectors.[277] The US Environmental Protection Agency State Energy and Environment Guide to Action[278] provides guiding framework on how to represent climate change to utilities IRPs. Cooke et al. (2021)[279] reviewed best practices in consideration of climate change of IRPs in 40 electric utilities across the US, admitting an increased level of complexity in the process. While IRPs are not legally bounding, some states such as California and New York made legislation of some recommendations. State-scale vulnerability assessments are also leveraged to develop legislation (KMs 21.4, 32.5).

The reduction of uncertainty of future climate projections is essential for future planning, human adaptation, and increasing energy system resilience, and a number of studies have demonstrated progres s.[195,196,201,209,210,280,281,282,283,284,285] Fragility curves of damage to power generating stations (coal, gas, solar, wind) and electrical grid components, as well as replacement and repair costs under hurricane scenarios, have also been developed.[204] Even in contexts where climate projections are uncertain, modeling advancements are helpful for planning; for example, modeling synthetic storms provides extreme wind and wave loads required for planning of offshore wind energy.[14]

Research is ongoing to identify needs for hardening[24] and to reduce the vulnerability of conventional energy system technologies to climate change.[191] For example, a range of studies reflects ongoing efforts by the oil and gas sector to address the challenge of a warming climate in Alaska, including technological improvements implemented in seismic exploration, operation and maintenance practices, and other improvements (e.g., use of thermosiphons, or cooling devices that will chill the ground beneath oil and gas infrastructure to provide protection from the dangers of thawing permafrost).

Significant innovations and deployment of zero-carbon electricity generation technologies are occurring, including in solar photovoltaics and on- and offshore wind. The costs and performance of batteries and long-term storage also are improving as their capacity grows to support the integration of renewables.[190] Advanced nuclear technologies (small modular reactors and microreactors) are now being demonstrated. Studies demonstrate innovative research, development, demonstration, and deployment to address large-scale carbon management. These include applications of CCUS at power plants and industries, as well as an expanding focus on carbon dioxide removal from the atmosphere through direct air capture and bioenergy with carbon capture and storage.[286,287] In addition, advances in low-carbon fuel sources can complement clean electricity, such as hydrogen (i.e., made from natural gas with CCUS or by electrolysis of water using zero-carbon electricity sources) to replace the role currently played by natural gas.

On the demand side, there is evidence of progress in reducing carbon through electrification. This evidence includes increased marketing and sales of electric vehicles and deployment of charging stations.[115,288] In addition, federal policies (e.g., efficiency and emission standards) and incentives (e.g., electric vehicle tax credits) appear to be succeeding in reducing use of fossil fuels. Furthermore, power companies are

evaluating how electric vehicles can improve resilience of the electric grid to extreme events by providing backup power during power outages.

Studies demonstrate how new technologies, cost reductions, and a range of enabling state and federal policies are contributing to the transition to a clean energy system (Chs. 25, 32).[4,5,7,8,9,10,11] However, there is inconsistency in the adoption of these policies across the Nation. For example, some states and local communities are adopting building codes, incentives, and bans to shift to clean energy sources,[10,11] while other states are adopting polices that would prohibit actions necessary to reduce GHG emissions, such as prohibiting restrictions on the use of fossil fuels. While progress is underway, actions vary from state to state in establishing an enabling policy framework to increase the pace, scale, and scope of the energy transition to deliver more clean energy and build a more resilient energy future.

## Major Uncertainties and Research Gaps

Research on energy resilience, including current approaches and future methods, has gaps. Much of the resilience and long-term power planning research to date has included case studies developed in silos, and there is a need to further integrate the range of models and associated recommendations on decision-making.[289] For example, effects of increased renewables penetration on electricity system resilience, including planning, response, and restoration, are not well studied.[177] Information is limited on the implications of measures that communities are using to increase resilience to extreme events. During power outages, remote or island communities often turn to backup diesel generation for increased power. However, data on the types of measures employed and costs and benefits associated with these backup options are often lacking in current analyses. Research efforts more specific to power system models include the development of next-generation tools to create multiscale cross-domain dependencies with a strategic computational efficiency for faster adoption, which will enhance the ability to plan for the unpredictable including extreme events and cyberattacks.[289]

Much effort is ongoing in the development of Earth system models that could inform the energy sector, including the regional refined mesh capabilities to enable high-resolution simulations in the region of interest in global settings.[290] In addition, while progress has been made in the energy–environmental–social science modeling, gaps remain in understanding the complex interactions.[210] Potential areas for study and development include the energy–water nexus. Specifically, technology innovation research includes cost-competitive desalination technologies, transforming produced water to a reusable resource, reducing water impacts in the power sector, increasing resource recovery from wastewater, and developing small, modular energy–water systems.[291] Projections of future energy infrastructure under current policies as well as decarbonization pathways now systematically investigate water demands across sectors,[292] as different technologies rely on either water withdrawals or consumptive use with complex interactions and coordination with other water uses. Higher-resolution modeling is needed to address regional institutional priorities and vulnerabilities.[293]

Energy justice is a relatively new research area. Whereas researchers are beginning to record and analyze distributional injustices (e.g., differential times to power restoration for different communities),[141,155,156] the lack of understanding of supply differences and vulnerability differences limits the ability for utilities and governments to study and develop fair policies and responses. Furthermore, data at finer resolution than the census tract scale are often not available; therefore, local distributional injustices are more uncertain than injustices occurring at larger spatial scales.

Considerable research is being conducted using energy system optimization and integrated assessment models to understand the environmental impacts of various climate change mitigation strategies, including on co-emitted pollutants and air quality,[247] as well as on labor and crop impacts.[294] While these studies tend to suggest air quality benefits associated with decarbonization, some suggest that there could be shifts in

the location of pollution and potentially the introduction of new sources of air pollution.[257] Opportunities exist to improve our understanding of the air pollutant emissions associated with decarbonization technologies, the degree to which these emissions can be controlled, and the role of permitting and environmental regulations on influencing siting and control decisions. There are also opportunities for more fully understanding how the resulting changes affect vulnerable populations, such as how changes in air-pollutant emissions result in changes in neighborhood-scale impacts.

Life-cycle analysis methods can be used to provide insights into the relative environmental benefits of alternative climate change mitigation technologies and pathways, including the impacts of manufacturing energy technologies and the construction of energy infrastructure.[295] A research gap in more fully understanding environmental impacts of energy transitions could be addressed by linking life-cycle analysis methods with energy system and integrated assessment models.[254,296]

## Description of Confidence and Likelihood

Research by authors in government, academia, and the private sector has produced evidence that allows the authors to conclude with *very high confidence* that enhancements in the resilience of the energy system to climate-related stressors are being made, including improvements in energy-efficient buildings; technology to decarbonize the energy system; advanced automation and communication, artificial intelligence, and machine learning technologies to optimize operations; climate modeling capabilities and planning methodologies; efforts to increase equitable access to clean energy; and federal support to communities for resilience investments. There is *very high confidence* that opportunities exist to build upon these efforts and that increases in the pace, scale, and scope of these efforts would be needed to meet the climate crisis.[87,232,233,236]

# References


1. NOAA, 2023: Greenhouse gases continued to increase rapidly in 2022. National Oceanic and Atmospheric Administration, April 5, 2023. https://www.noaa.gov/news-release/greenhouse-gases-continued-to-increase-rapidly-in-2022

2. EIA, 2021: U.S. Energy-Related Carbon Dioxide, 2021. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/environment/emissions/carbon/pdf/2021_co2analysis.pdf

3. EIA, 2023: Annual Energy Outlook 2023. AEO2023 Narrative. U.S. Energy Information Administration. https://www.eia.gov/outlooks/aeo/pdf/aeo2023_narrative.pdf

4. Infrastructure Investment and Jobs Act. 117th Congress, Pub. L. No. 117-58, 135 Stat. 429, November 15, 2021. https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf

5. nflation Reduction Act of 2022. 117th Congress, Pub. L. No. 117-169, 136 Stat. 1818, August 16, 2022. https://www.congress.gov/bill/117th-congress/house-bill/5376/text

6. DOE, 2022: The Inflation Reduction Act Drives Significant Emissions Reductions and Positions America to Reach our Climate Goals. DOE/OP-0018. U.S. Department of Energy, Office of Policy, 6 pp. https://www.energy.gov/sites/default/files/2022-08/8.18%20InflationReductionAct_Factsheet_Final.pdf

7. IEA, 2023: World Energy Investment 2023. International Energy Agency, Paris, France. https://www.iea.org/reports/world-energy-investment-2023

8. Steinberg, D.C., M. Brown, R. Wiser, P. Donohoo-Vallett, P. Gagnon, A. Hamilton, M. Mowers, C. Murphy, and A. Prasana, 2023: Evaluating Impacts of the Inflation Reduction Act and Bipartisan Infrastructure Law on the U.S. Power System. NREL/TP-6A20-85242. U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO. https://www.nrel.gov/docs/fy23osti/85242.pdf

9. CRS, 2022: Inflation Reduction Act of 2022 (IRA): Provisions Related to Climate Change. CRS Report R47262. Congressional Research Service. https://crsreports.congress.gov/product/pdf/r/r47262

10. To Amend the Administrative Code of the City of New York, in Relation to the Use of Substances with Certain Emissions Profiles. Local Law No. 154 of 2021, Council Int. No. 2317-A of 2021, City of New York, December 22, 2021. http://www.nyc.gov/assets/buildings/local_laws/ll154of2021.pdf

11. CEC, 2022: 2022 Building Energy Efficiency Standards. California Energy Commission. https://www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards/2022-building-energy-efficiency

12. DOE, 2013: U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather. U.S. Department of Energy. https://www.energy.gov/articles/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather

13. Hashemi, M.R., B. Kresning, J. Hashemi, and I. Ginis, 2021: Assessment of hurricane generated loads on o□shore wind farms: A closer look at most extreme historical hurricanes in New England. *Renewable Energy*, **175**, 593–609. https://doi.org/10.1016/j.renene.2021.05.042

14. Kresning, B., M. Reza Hashemi, and C. Gallucci, 2020: Simulation of hurricane loading for proposed offshore windfarms off the US Northeast coast. *Journal of Physics: Conference Series*, **1452** (1), 012026. https://doi.org/10.1088/1742-6596/1452/1/012026

15. Davlasheridze, M., Q. Fan, W. Highfield, and J. Liang, 2021: Economic impacts of storm surge events: Examining state and national ripple effects. *Climatic Change*, **166** (1), 11. https://doi.org/10.1007/s10584-021-03106-z

16. EIA, 2022: Gulf of Mexico Fact Sheet. U.S. Energy Information Administration, Washington, DC. http://www.eia.gov/special/gulf_of_mexico/

17. Cinner, J.E., W.N. Adger, E.H. Allison, M.L. Barnes, K. Brown, P.J. Cohen, S. Gelcich, C.C. Hicks, T.P. Hughes, J. Lau, N.A. Marshall, and T.H. Morrison, 2018: Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change*, **8** (2), 117–123. https://doi.org/10.1038/s41558-017-0065-x

18. Hinkel, J., J.C.J.H. Aerts, S. Brown, J.A. Jiménez, D. Lincke, R.J. Nicholls, P. Scussolini, A. Sanchez-Arcilla, A. Vafeidis, and K.A. Addo, 2018: The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, **8** (7), 570–578. https://doi.org/10.1038/s41558-018-0176-z

19. Balch, J.K., J.T. Abatzoglou, M.B. Joseph, M.J. Koontz, A.L. Mahood, J. McGlinchy, M.E. Cattau, and A.P. Williams, 2022: Warming weakens the night-time barrier to global fire. *Nature*, **602** (7897), 442–448. https://doi.org/10.1038/s41586-021-04325-1

20. Muhs, J.W., M. Parvania, and M. Shahidehpour, 2020: Wildfire risk mitigation: A paradigm shift in power systems planning and operation. *Journal of Power and Energy*, **7**, 366–375. https://doi.org/10.1109/oajpe.2020.3030023

21. Donaldson, D.L., D.M. Piper, and D. Jayaweera, 2021: Temporal solar photovoltaic generation capacity reduction from wildfire smoke. *IEEE Access*, **9**, 79841–79852. https://doi.org/10.1109/access.2021.3084528

22. Gilletly, S.D., N.D. Jackson, and A. Staid, 2021: Quantifying wildfire-induced impacts to photovoltaic energy production in the western United States. In: *2021 IEEE 48th Photovoltaic Specialists Conference* (PVSC). Fort Lauderdale, FL, 20–25 June 2021. IEEE, 1619–1625. https://doi.org/10.1109/pvsc43889.2021.9518514

23. Muehleisen, W., G.C. Eder, Y. Voronko, M. Spielberger, H. Sonnleitner, K. Knoebl, R. Ebner, G. Ujvari, and C. Hirschl, 2018: Outdoor detection and visualization of hailstorm damages of photovoltaic plants. *Renewable Energy*, **118**, 138–145. https://doi.org/10.1016/j.renene.2017.11.010

24. Busby, J.W., K. Baker, M.D. Bazilian, A.Q. Gilbert, E. Grubert, V. Rai, J.D. Rhods, S. Shidore, C.A. Smith, and M.E. Webber, 2021: Cascading risks: Understanding the 2021 winter blackout in Texas. *Energy Research & Social Science*, **77**, 102106. https://doi.org/10.1016/j.erss.2021.102106

25. Allen-Dumas, M., B. Kc, and C.I. Cunliff, 2019: Extreme Weather and Climate Vulnerabilities of the Electric Grid: A Summary of Environmental Sensitivity Quantification Methods. ORNL/TM-2019/1252. U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN. https://doi.org/10.2172/1558514

26. Murphy, S., L. Lavin, and J. Apt, 2020: Resource adequacy implications of temperature-dependent electric generator availability. *Applied Energy*, **262**, 114424. https://doi.org/10.1016/j.apenergy.2019.114424

27. Ahmad, A., 2021: Increase in frequency of nuclear power outages due to changing climate. *Nature Energy*, **6** (7), 755–762. https://doi.org/10.1038/s41560-021-00849-y

28. Morrow, W.R., A. Gopal, G. Fitts, S. Lewis, L. Dale, and E. Masanet, 2014: Feedstock loss from drought is a major economic risk for biofuel producers. *Biomass and Bioenergy*, **69**, 135–143. https://doi.org/10.1016/j.biombioe.2014.05.006

29. Coburn, J. and S.C. Pryor, 2023: Projecting future energy production from operating wind farms in North America. Part II: Statistical downscaling. *Journal of Applied Meteorology and Climatology*, **62** (1), 81–101. https://doi.org/10.1175/jamc-d-22-0047.1

30. Gernaat, D.E.H.J., H.S. de Boer, V. Daioglou, S.G. Yalew, C. Müller, and D.P. van Vuuren, 2021: Climate change impacts on renewable energy supply. *Nature Climate Change*, **11** (2), 119–125. https://doi.org/10.1038/s41558-020-00949-9

31. Karnauskas, K.B., J.K. Lundquist, and L. Zhang, 2018: Southward shift of the global wind energy resource under high carbon dioxide emissions. *Nature Geoscience*, **11** (1), 38–43. https://doi.org/10.1038/s41561-017-0029-9

32. Losada Carreño, I., M.T. Craig, M. Rossol, M. Ashfaq, F. Batibeniz, S.E. Haupt, C. Draxl, B.-M. Hodge, and C. Brancucci, 2020: Potential impacts of climate change on wind and solar electricity generation in Texas. *Climatic Change*, **163** (2), 745–766. https://doi.org/10.1007/s10584-020-02891-3

33. Solaun, K. and E. Cerdá, 2019: Climate change impacts on renewable energy generation. A review of quantitative projections. *Renewable and Sustainable Energy Reviews*, **116**, 109415. https://doi.org/10.1016/j.rser.2019.109415

34. Yin, J., A. Molini, and A. Porporato, 2020: Impacts of solar intermittency on future photovoltaic reliability. *Nature Communications*, **11** (1), 4781. https://doi.org/10.1038/s41467-020-18602-6

35. Bukhary, S., S. Ahmad, and J. Batista, 2018: Analyzing land and water requirements for solar deployment in the Southwestern United States. *Renewable and Sustainable Energy Reviews*, **82**, 3288–3305. https://doi.org/10.1016/j.rser.2017.10.016

36. EIA, 2021: Electricity Data Browser: Net Generation, Conventional Hydroelectric, All Sectors, Annual. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/electricity/data/browser/

37. EIA, 2022: Today in Energy: California Drought Could Reduce Hydroelectric Generation to Half of Normal Levels. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/todayinenergy/detail.php?id=52578

38. Voisin, N., A. Dyreson, T. Fu, M. O'Connell, S.W.D. Turner, T. Zhou, and J. Macknick, 2020: Impact of climate change on water availability and its propagation through the western U.S. power grid. *Applied Energy*, **276**, 115467. https://doi.org/10.1016/j.apenergy.2020.115467

39. Webster, M., K. Fisher-Vanden, V. Kumar, R.B. Lammers, and J. Perla, 2022: Integrated hydrological, power system and economic modelling of climate impacts on electricity demand and cost. *Nature Energy*, **7** (2), 163–169. https://doi.org/10.1038/s41560-021-00958-8

40. Zhao, G., H. Gao, and S.-C. Kao, 2021: The implications of future climate change on the blue water footprint of hydropower in the contiguous US. *Environmental Research Letters*, **16** (3), 034003. https://doi.org/10.1088/1748-9326/abd78d

41. Sharma, S., J. Waldman, S. Afshari, and B. Fekete, 2019: Status, trends and significance of American hydropower in the changing energy landscape. *Renewable and Sustainable Energy Reviews*, **101**, 112–122. https://doi.org/10.1016/j.rser.2018.10.028

42. Brown, T.C., V. Mahat, and J.A. Ramirez, 2019: Adaptation to future water shortages in the United States caused by population growth and climate change. *Earth's Future*, **7** (3), 219–234. https://doi.org/10.1029/2018ef001091

43. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. https://doi.org/10.1038/s41558-022-01290-z

44. Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, J.T. Abatzoglou, K. Bolles, S.H. Baek, A.M. Badger, and B. Livneh, 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368** (6488), 314–318. https://doi.org/10.1126/science.aaz9600

45. Kao, S.C., M. Ashfaq, D. Rastogi, S. Gangrade, R.U. Martinez, A. Fernandez, G. Konapala, N. Voisin, T. Zhou, W. Xu, H. Gao, B. Zhao, and C. Zhao, 2022: The Third Assessment of the Effects of Climate Change on Federal Hydropower. ORNL/TM-2021/2278. U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN. https://doi.org/10.2172/1887712

46. Turner, S.W.D., N. Voisin, J. Fazio, D. Hua, and M. Jourabchi, 2019: Compound climate events transform electrical power shortfall risk in the Pacific Northwest. *Nature Communications*, **10** (1), 8. https://doi.org/10.1038/s41467-018-07894-4

47. EIA, 2021: Electricity Explained: How Electricity is Generated. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/energyexplained/electricity/how-electricity-is-generated.php

48. Grubert, E. and K.T. Sanders, 2018: Water use in the United States energy system: A national assessment and unit process inventory of water consumption and withdrawals. *Environmental Science & Technology*, **52** (11), 6695–6703. https://doi.org/10.1021/acs.est.8b00139

49. Sanders, K.T., 2015: Critical review: Uncharted waters? The future of the electricity-water nexus. *Environmental Science & Technology*, **49** (1), 51–66. https://doi.org/10.1021/es504293b

50. Rosa, L., D.L. Sanchez, G. Realmonte, D. Baldocchi, and P. D'Odorico, 2021: The water footprint of carbon capture and storage technologies. *Renewable and Sustainable Energy Reviews*, **138**, 110511. https://doi.org/10.1016/j.rser.2020.110511

51. Mays, G., 2021: Ch. 21. Small modular reactors (SMRs): The case of the United States of America. In: *Handbook of Small Modular Nuclear Reactors*, 2nd ed. Ingersoll, D.T. and M.D. Carelli, Eds. Woodhead Publishing, 521–553. https://doi.org/10.1016/b978-0-12-823916-2.00021-7

52. Cheng, Y., N. Voisin, J.R. Yearsley, and B. Nijssen, 2020: Thermal extremes in regulated river systems under climate change: An application to the southeastern U.S. rivers. *Environmental Research Letters*, **15** (9), 094012. https://doi.org/10.1088/1748-9326/ab8f5f

53. Liu, L., M. Hejazi, H. Li, B. Forman, and X. Zhang, 2017: Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations. *Nature Energy*, **2** (8), 17109. https://doi.org/10.1038/nenergy.2017.109

54. Miara, A., J.E. Macknick, C.J. Vörösmarty, V.C. Tidwell, R. Newmark, and B. Fekete, 2017: Climate and water resource change impacts and adaptation potential for US power supply. *Nature Climate Change*, **7** (11), 793–798. https://doi.org/10.1038/nclimate3417

55. Turner, S.W.D., K. Nelson, N. Voisin, V. Tidwell, A. Miara, A. Dyreson, S. Cohen, D. Mantena, J. Jin, P. Warnken, and S.-C. Kao, 2021: A multi-reservoir model for projecting drought impacts on thermoelectric disruption risk across the Texas power grid. *Energy*, **231**, 120892. https://doi.org/10.1016/j.energy.2021.120892

56. Climate Central, 2022: Climate Matters: Surging Weather-related Power Outages [Webpage]. https://www.climatecentral.org/climate-matters/surging-weather-related-power-outages

57. Fant, C., B. Boehlert, K. Strzepek, P. Larsen, A. White, S. Gulati, Y. Li, and J. Martinich, 2020: Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure. *Energy*, **195**, 116899. https://doi.org/10.1016/j.energy.2020.116899

58. Emerton, R., C. Brimicombe, L. Magnusson, C. Roberts, C. Di Napoli, H.L. Cloke, and F. Pappenberger, 2022: Predicting the unprecedented: Forecasting the June 2021 Pacific Northwest heatwave. *Weather*, **77** (8), 272–279. https://doi.org/10.1002/wea.4257

59. Song, F., G.J. Zhang, V. Ramanathan, and L.R. Leung, 2022: Trends in surface equivalent potential temperature: A more comprehensive metric for global warming and weather extremes. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (6), e2117832119. https://doi.org/10.1073/pnas.2117832119

60. Bartos, M., M. Chester, N. Johnson, B. Gorman, D. Eisenberg, I. Linkov, and M. Bates, 2016: Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States. *Environmental Research Letters*, **11** (11), 114008. https://doi.org/10.1088/1748-9326/11/11/114008

61. Coleman, N., A. Esmalian, C.-C. Lee, E. Gonzales, P. Koirala, and A. Mostafavi, 2023: Energy inequality in climate hazards: Empirical evidence of social and spatial disparities in managed and hazard-induced power outages. *Sustainable Cities and Society*, **92**, 104491. https://doi.org/10.1016/j.scs.2023.104491

62. EIA, 2021: Today in Energy: U.S. Electricity Customers Experienced Eight Hours of Power Interruptions in 2020. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/todayinenergy/detail.php?id=50316

63. Nazaripouya, H., 2020: Power grid resilience under wildfire: A review on challenges and solutions. In: 2020 *IEEE Power & Energy Society General Meeting* (PESGM). Montreal, QC, Canada, 2–6 August 2020. IEEE. https://doi.org/10.1109/pesgm41954.2020.9281708

64. Panteli, M. and P. Mancarella, 2015: Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research*, **127**, 259–270. https://doi.org/10.1016/j.epsr.2015.06.012

65. Cerrai, D., D.W. Wanik, M.A.E. Bhuiyan, X. Zhang, J. Yang, M.E.B. Frediani, and E.N. Anagnostou, 2019: Predicting storm outages through new representations of weather and vegetation. *IEEE Access*, **7**, 29639–29654. https://doi.org/10.1109/access.2019.2902558

66. D'Amico, D.F., S.M. Quiring, C.M. Maderia, and D.B. McRoberts, 2019: Improving the Hurricane Outage Prediction Model by including tree species. *Climate Risk Management*, **25**, 100193. https://doi.org/10.1016/j.crm.2019.100193

67. Brettschneider, S. and I. Fofana, 2021: Evolution of countermeasures against atmospheric icing of power lines over the past four decades and their applications into field operations. *Energies*, **14** (19), 6291. https://doi.org/10.3390/en14196291

68. Arab, A., A. Khodaei, R. Eskandarpour, M.P. Thompson, and Y. Wei, 2021: Three lines of defense for wildfire risk management in electric power grids: A review. *IEEE Access*, **9**, 61577–61593. https://doi.org/10.1109/access.2021.3074477

69. Oruji, S., M. Ketabdar, D. Moon, V. Tsao, and M. Ketabdar, 2022: Evaluation of land subsidence hazard on steel natural gas pipelines in California. *Upstream Oil and Gas Technology*, **8**, 100062. https://doi.org/10.1016/j.upstre.2021.100062

70. de Bruijn, K.M., C. Maran, M. Zygnerski, J. Jurado, A. Burzel, C. Jeuken, and J. Obeysekera, 2019: Flood resilience of critical infrastructure: Approach and method applied to Fort Lauderdale, Florida. *Water*, **11** (3), 517. https://doi.org/10.3390/w11030517

71. Khanam, M., G. Sofia, M. Koukoula, R. Lazin, E.I. Nikolopoulos, X. Shen, and E.N. Anagnostou, 2021: Impact of compound flood event on coastal critical infrastructures considering current and future climate. *Natural Hazards and Earth System Sciences*, **21** (2), 587–605. https://doi.org/10.5194/nhess-21-587-2021

72. Kwasinski, A., F. Andrade, M.J. Castro-Sitiriche, and E. O'Neill-Carrillo, 2019: Hurricane Maria effects on Puerto Rico electric power infrastructure. *IEEE Power and Energy Technology Systems Journal*, **6** (1), 85–94. https://doi.org/10.1109/jpets.2019.2900293

73. Abatzoglou, J.T., C.M. Smith, D.L. Swain, T. Ptak, and C.A. Kolden, 2020: Population exposure to pre-emptive de-energization aimed at averting wildfires in Northern California. *Environmental Research Letters*, **15**, 094046. https://doi.org/10.1088/1748-9326/aba135

74. Rhodes, N., L. Ntaimo, and L. Roald, 2021: Balancing wildfire risk and power outages through optimized power shut-offs. *IEEE Transactions on Power Systems*, **36** (4), 3118–3128. https://doi.org/10.1109/tpwrs.2020.3046796

75. Antoniou, A., A. Dimou, E. Zacharis, F. Konstantopoulou, and P. Karvelis, 2020: Adapting oil & gas infrastructures to climate change. *Pipeline Technology Journal*. https://www.pipeline-journal.net/articles/adapting-oil-gas-infrastructures-climate-change

76. National Academies of Sciences, Engineering, and Medicine, 2020: *Strengthening Post-Hurricane Supply Chain Resilience: Observations from Hurricanes Harvey, Irma, and Maria*. The National Academies Press, Washington, DC, 136 pp. https://doi.org/10.17226/25490

77. Ni, W., Y. Liang, Z. Li, Q. Liao, S. Cai, B. Wang, H. Zhang, and Y. Wang, 2022: Resilience assessment of the downstream oil supply chain considering the inventory strategy in extreme weather events. *Computers & Chemical Engineering*, **163**, 107831. https://doi.org/10.1016/j.compchemeng.2022.107831

78. Sichani, M.E. and J.E. Padgett, 2021: Performance assessment of oil supply chain infrastructure subjected to hurricanes. *Journal of Infrastructure Systems*, **27** (4), 04021033. https://doi.org/10.1061/(asce)is.1943-555x.0000637

79. Dong, J., Z. Asif, Y. Shi, Y. Zhu, and Z. Chen, 2022: Climate change impacts on coastal and offshore petroleum infrastructure and the associated oil spill risk: A review. *Journal of Marine Science and Engineering*, **10** (7), 849. https://doi.org/10.3390/jmse10070849

80. EIA, 2022: Oil and Petroleum Products Explained: Use of Oil. U.S. Energy Information Administration. https://www.eia.gov/energyexplained/oil-and-petroleum-products/use-of-oil.php

81. EIA, 2020: Today in Energy: Hurricane Laura Shut in More Gulf of Mexico Crude Oil Production Than Any Storm Since 2008. U.S. Energy Information Administration, Washington, DC, accessed October 2, 2020. https://www.eia.gov/todayinenergy/detail.php?id=45376

82. Davis, A., D. Thrift-Viveros, and C.M.S. Baker, 2021: NOAA scientific support for a natural gas pipeline release during Hurricane Harvey flooding in the Neches River Beaumont, Texas. *International Oil Spill Conference Proceedings*, **2021** (1), 687018. https://doi.org/10.7901/2169-3358-2021.1.687018

83. Qin, R., N. Khakzad, and J. Zhu, 2020: An overview of the impact of Hurricane Harvey on chemical and process facilities in Texas. *International Journal of Disaster Risk Reduction*, **45**, 101453. https://doi.org/10.1016/j.ijdrr.2019.101453

84. GAO, 2021: Offshore Oil and Gas: Updated Regulations Needed to Improve Pipeline Oversight and Decommissioning. GAO-21-293. U.S. Government Accountability Office. https://www.gao.gov/products/gao-21-293

85. Doss-Gollin, J., D.J. Farnham, U. Lall, and V. Modi, 2021: How unprecedented was the February 2021 Texas cold snap? *Environmental Research Letters*, **16** (6), 064056. https://doi.org/10.1088/1748-9326/ac0278

86. Speake, A., P. Donohoo-Vallett, E. Wilson, E. Chen, and C. Christensen, 2020: Residential natural gas demand response potential during extreme cold events in electricity-gas coupled energy systems. *Energies*, **13** (19), 5192. https://doi.org/10.3390/en13195192

87. IPCC, 2021: Summary for policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–32. https://doi.org/10.1017/9781009157896.001

88. Ileri, E.C., H. Her, A. Mazounie, and L. Pinson, 2021: DRILL, BABY, DRILL: How Banks, Investors and Insurers Are Driving Oil and Gas Expansion in the Arctic. Reclaim Finance. https://reclaimfinance.org/site/wp-content/uploads/2021/09/Drill_Baby_Drill_RF_Arctic_Report_23_09_2021.pdf

89. Zamuda, C., D.E. Bilello, G. Conzelmann, E. Mecray, A. Satsangi, V. Tidwell, and B.J. Walker, 2018: Ch. 4. Energy supply, delivery, and demand. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 174–201. https://doi.org/10.7930/nca4.2018.ch4

90. Gädeke, A., M. Langer, J. Boike, E.J. Burke, J. Chang, M. Head, C.P.O. Reyer, S. Schaphoff, W. Thiery, and K. Thonicke, 2021: Climate change reduces winter overland travel across the Pan-Arctic even under low-end global warming scenarios. *Environmental Research Letters*, **16** (2), 024049. https://doi.org/10.1088/1748-9326/abdcf2

91. Hori, Y., V.Y.S. Cheng, W.A. Gough, J.Y. Jien, and L.J.S. Tsuji, 2018: Implications of projected climate change on winter road systems in Ontario's Far North, Canada. *Climatic Change*, **148** (1), 109–122. https://doi.org/10.1007/s10584-018-2178-2

92. EIA, 2023: AEO2023 Issues in Focus: Inflation Reduction Act Cases in the AEO2023. U.S. Department of Energy, U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/outlooks/aeo/iif_ira/pdf/ira_iif.pdf

93. Zhou, E. and T. Mai, 2021: Electrification Futures Study: Operational Analysis of U.S. Power Systems with Increased Electrification and Demand-Side Flexibility. NREL/TP-6A20-79094. U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO. https://www.nrel.gov/docs/fy21osti/79094.pdf

94. Bistline, J.E.T., C.W. Roney, D.L. McCollum, and G.J. Blanford, 2021: Deep decarbonization impacts on electric load shapes and peak demand. *Environmental Research Letters*, **16** (9), 094054. https://doi.org/10.1088/1748-9326/ac2197

95. EPRI, 2018: U.S. National Electrification Assessment. Electric Power Research Institute. https://www.epri.com/research/products/000000003002013582

96. EPRI, 2021: Strategies and Actions for Achieving a 50% Reduction in U.S. Greenhouse Gas Emissions by 2030. Electric Power Research Institute, Palo Alto, CA. https://www.epri.com/research/products/000000003002023165

97. Khan, Z., M. Zhao, H. Ahsan, P. Wolfram, A. Snyder, P. Kyle, J. Rice, C. Vernon, Y. Ou, M. Binsted, and G. Iyer. 2023: Version of GCAM-USA used for National Climate Assessment 5, Chapter 5: GCAM-USA-v5.3-IM3-NCA5. MSD-LIVE Data Repository. https://doi.org/10.57931/1963007

98. Murphy, C., T. Mai, E. Zhou, M. Muratori, and P. Jadun, 2022: Electrification futures study. In: *Electrify the Big Sky Conference*. Missoula, MT. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, National Renewable Energy Laboratory. https://www.osti.gov/biblio/1888234

99. Khan, Z., G. Iyer, P. Patel, S. Kim, M. Hejazi, C. Burleyson, and M. Wise, 2021: Impacts of long-term temperature change and variability on electricity investments. *Nature Communications*, **12** (1), 1643. https://doi.org/10.1038/s41467-021-21785-1

100. Obringer, R., R. Nateghi, D. Maia-Silva, S. Mukherjee, V. Cr, D.B. McRoberts, and R. Kumar, 2022: Implications of increasing household air conditioning use across the United States under a warming climate. *Earth's Future*, **10** (1), e2021EF002434. https://doi.org/10.1029/2021ef002434

101. Ralston Fonseca, F., P. Jaramillo, M. Bergés, and E. Severnini, 2019: Seasonal effects of climate change on intra-day electricity demand patterns. *Climatic Change*, **154** (3), 435–451. https://doi.org/10.1007/s10584-019-02413-w

102. van Ruijven, B.J., E. De Cian, and I. Sue Wing, 2019: Amplification of future energy demand growth due to climate change. *Nature Communications*, **10** (1), 2762. https://doi.org/10.1038/s41467-019-10399-3

103. Rastogi, D., J.S. Holladay, K.J. Evans, B.L. Preston, and M. Ashfaq, 2019: Shift in seasonal climate patterns likely to impact residential energy consumption in the United States. *Environmental Research Letters*, **14** (7), 074006. https://doi.org/10.1088/1748-9326/ab22d2

104. Ortiz, L., J.E. González, and W. Lin, 2018: Climate change impacts on peak building cooling energy demand in a coastal megacity. *Environmental Research Letters*, **13** (9), 094008. https://doi.org/10.1088/1748-9326/aad8d0

105. Wang, Z., T. Hong, H. Li, and M. Ann Piette, 2021: Predicting city-scale daily electricity consumption using data-driven models. *Advances in Applied Energy*, **2**, 100025. https://doi.org/10.1016/j.adapen.2021.100025

106. Overland, J.E., 2021: Causes of the record-breaking Pacific Northwest heatwave, late June 2021. *Atmosphere*, **12** (11), 1434. https://doi.org/10.3390/atmos12111434

107. EIA, 2021: Today in Energy: June Heat Wave in the Northwest United States Resulted in More Demand for Electricity. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/todayinenergy/detail.php?id=48796

108. Rempel, A.R., J. Danis, A.W. Rempel, M. Fowler, and S. Mishra, 2022: Improving the passive survivability of residential buildings during extreme heat events in the Pacific Northwest. *Applied Energy*, **321**, 119323. https://doi.org/10.1016/j.apenergy.2022.119323

109. Bistline, J., N. Abhyankar, G. Blanford, L. Clarke, R. Fakhry, H. McJeon, J. Reilly, C. Roney, T. Wilson, M. Yuan, and A. Zhao, 2022: Actions for reducing US emissions at least 50% by 2030. *Science*, **376** (6596), 922–924. https://doi.org/10.1126/science.abn0661

110. Mai, T.T., P. Jadun, J.S. Logan, C.A. McMillan, M. Muratori, D.C. Steinberg, L.J. Vimmerstedt, B. Haley, R. Jones, and B. Nelson, 2018: Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States. NREL/TP-6A20-71500. U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO. https://doi.org/10.2172/1459351

111. Muratori, M., M. Alexander, D. Arent, M. Bazilian, P. Cazzola, E.M. Dede, J. Farrell, C. Gearhart, D. Greene, A. Jenn, M. Keyser, T. Lipman, S. Narumanchi, A. Pesaran, R. Sioshansi, E. Suomalainen, G. Tal, K. Walkowicz, and J. Ward, 2021: The rise of electric vehicles—2020 status and future expectations. *Progress in Energy*, **3** (2), 022002. https://doi.org/10.1088/2516-1083/abe0ad

112. National Academies of Sciences, Engineering, and Medicine, 2021: *Accelerating Decarbonization of the U.S. Energy System*. The National Academies Press, Washington, DC, 268 pp. https://doi.org/10.17226/25932

113. Rightor, E., A. Whitlock, and N. Elliot, 2020: Beneficial Electrification in Industry. American Council for an Energy-Efficient Economy. https://www.aceee.org/research-report/ie2002

114. Langevin, J., C.B. Harris, A. Satre-Meloy, H. Chandra-Putra, A. Speake, E. Present, R. Adhikari, E.J.H. Wilson, and A.J. Satchwell, 2021: US building energy efficiency and flexibility as an electric grid resource. *Joule*, **5** (8), 2102–2128. https://doi.org/10.1016/j.joule.2021.06.002

115. Cheng, A.J., B. Tarroja, B. Shaffer, and S. Samuelsen, 2018: Comparing the emissions benefits of centralized vs. decentralized electric vehicle smart charging approaches: A case study of the year 2030 California electric grid. *Journal of Power Sources*, **401**, 175–185. https://doi.org/10.1016/j.jpowsour.2018.08.092

116. DOE, 2022: Clean Hydrogen Production Standard (CHPS) Draft Guidance. U.S. Department of Energy. https://www.energy.gov/eere/fuelcells/articles/clean-hydrogen-production-standard

117. Oliveira, A.M., R.R. Beswick, and Y. Yan, 2021: A green hydrogen economy for a renewable energy society. *Current Opinion in Chemical Engineering*, **33**, 100701. https://doi.org/10.1016/j.coche.2021.100701

118. Rose, S.K., N. Bauer, A. Popp, J. Weyant, S. Fujimori, P. Havlik, M. Wise, and D.P. van Vuuren, 2020: An overview of the Energy Modeling Forum 33rd study: Assessing large-scale global bioenergy deployment for managing climate change. *Climatic Change*, **163** (3), 1539–1551. https://doi.org/10.1007/s10584-020-02945-6

119. Thombs, R.P., 2019: When democracy meets energy transitions: A typology of social power and energy system scale. *Energy Research & Social Science*, **52**, 159–168. https://doi.org/10.1016/j.erss.2019.02.020

120. Fajardy, M. and N. Mac Dowell, 2017: Can BECCS deliver sustainable and resource efficient negative emissions? *Energy and Environmental Science*, **10** (6), 1389–1426. https://doi.org/10.1039/c7ee00465f

121. Greig, C. and S. Uden, 2021: The value of CCUS in transitions to net-zero emissions. *The Electricity Journal*, **34** (7), 107004. https://doi.org/10.1016/j.tej.2021.107004

122. Arent, D.J., P. Green, Z. Abdullah, T. Barnes, S. Bauer, A. Bernstein, D. Berry, J. Berry, T. Burrell, B. Carpenter, J. Cochran, R. Cortright, M. Curry-Nkansah, P. Denholm, V. Gevorian, M. Himmel, B. Livingood, M. Keyser, J. King, B. Kroposki, T. Mai, M. Mehos, M. Muratori, S. Narumanchi, B. Pivovar, P. Romero-Lankao, M. Ruth, G. Stark, and C. Turchi, 2022: Challenges and opportunities in decarbonizing the U.S. energy system. *Renewable and Sustainable Energy Reviews*, **169**, 112939. https://doi.org/10.1016/j.rser.2022.112939

123. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.001

124. NREL, 2021: Electrification Futures Study. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, National Renewable Energy Laboratory. https://www.nrel.gov/analysis/electrification-futures.html

125. Gaines, L., K. Richa, and J. Spangenberger, 2018: Key issues for Li-ion battery recycling. *MRS Energy & Sustainability*, **5** (1), 12. https://doi.org/10.1557/mre.2018.13

126. Pereirinha, P.G., M. González, I. Carrilero, D. Anseán, J. Alonso, and J.C. Viera, 2018: Main trends and challenges in road transportation electrification. *Transportation Research Procedia*, **33**, 235–242. https://doi.org/10.1016/j.trpro.2018.10.096

127. Freitas, E.N., J.C. Salgado, R.C. Alnoch, A.G. Contato, E. Habermann, M. Michelin, C.A. Martínez, M. de Polizeli, and T.M. Lourdes, 2021: Challenges of biomass utilization for bioenergy in a climate change scenario. *Biology*, **10** (12). https://doi.org/10.3390/biology10121277

128. Chen, C.-f., X. Xu, J. Adams, J. Brannon, F. Li, and A. Walzem, 2020: When East meets West: Understanding residents' home energy management system adoption intention and willingness to pay in Japan and the United States. *Energy Research & Social Science*, **69**, 101616. https://doi.org/10.1016/j.erss.2020.101616

129. Goodarzi, S., A. Masini, S. Aflaki, and B. Fahimnia, 2021: Right information at the right time: Reevaluating the attitude–behavior gap in environmental technology adoption. *International Journal of Production Economics*, **242**, 108278. https://doi.org/10.1016/j.ijpe.2021.108278

130. Sharma, N., 2021: Public perceptions towards adoption of residential solar water heaters in USA: A case study of Phoenicians in Arizona. *Journal of Cleaner Production*, **320**, 128891. https://doi.org/10.1016/j.jclepro.2021.128891

131. Wolske, K.S., K.T. Gillingham, and P.W. Schultz, 2020: Peer influence on household energy behaviours. *Nature Energy*, **5** (3), 202–212. https://doi.org/10.1038/s41560-019-0541-9

132. Gillingham, K., D. Rapson, and G. Wagner, 2016: The rebound effect and energy efficiency policy. *Review of Environmental Economics and Policy*, **10** (1), 68–88. https://doi.org/10.1093/reep/rev017

133. Hald, K.S. and P. Coslugeanu, 2022: The preliminary supply chain lessons of the COVID-19 disruption—What is the role of digital technologies? *Operations Management Research*, **15** (1), 282–297. https://doi.org/10.1007/s12063-021-00207-x

134. Olabi, V., T. Wilberforce, K. Elsaid, E.T. Sayed, and M.A. Abdelkareem, 2022: Impact of COVID-19 on the renewable energy sector and mitigation strategies. *Chemical Engineering & Technology*, **45** (4), 558–571. https://doi.org/10.1002/ceat.202100504

135. Ballinger, B., M. Stringer, D.R. Schmeda-Lopez, B. Kefford, B. Parkinson, C. Greig, and S. Smart, 2019: The vulnerability of electric vehicle deployment to critical mineral supply. *Applied Energy*, **255**, 113844. https://doi.org/10.1016/j.apenergy.2019.113844

136. IEA, 2021: World Energy Outlook 2021. International Energy Agency, Paris, France. https://www.iea.org/reports/world-energy-outlook-2021

137. Kim, K. and L. Bui, 2019: Learning from Hurricane Maria: Island ports and supply chain resilience. *International Journal of Disaster Risk Reduction*, **39**, 101244. https://doi.org/10.1016/j.ijdrr.2019.101244

138. IEA, 2021: The Role of Critical Minerals in Clean Energy Transitions. International Energy Agency. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

139. The White House, 2021: Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth. The White House, Washington, DC, 250 pp. https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf

140. UNECE, 2021: Life Cycle Assessment of Electricity Generation Options. United Nations Economic Commission for Europe, Geneva, Switzerland. https://unece.org/sites/default/files/2021-11/LCA_final.pdf

141. Mitsova, D., A.-M. Esnard, A. Sapat, and B.S. Lai, 2018: Socioeconomic vulnerability and electric power restoration timelines in Florida: The case of Hurricane Irma. *Natural Hazards*, **94** (2), 689–709. https://doi.org/10.1007/s11069-018-3413-x

142. Hendricks, M.D. and S. Van Zandt, 2021: Unequal protection revisited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. *Environmental Justice*, **14** (2), 87–97. https://doi.org/10.1089/env.2020.0054

143. Howard, L., 2021: LIHEAP American Rescue Plan Funding: Racial and Economic Justice Is Also Equity in Energy. U.S. Department of Health and Human Services, Administration for Children and Families, Washington, DC. https://acfmain-dev.acf.hhs.gov/blog/2021/05/liheap-american-rescue-plan-funding-racial-economic-justice-also-equity-energy

144. PNNL, 2021: Energy Storage for Social Equity: Capturing Benefits from Power Plant Decommissioning. PNNL-31451. U.S. Department of Energy, Pacific Northwest National Laboratory. https://www.pnnl.gov/sites/default/files/media/file/Energy%20Storage%20for%20Social%20Equity%20Case%20Study.pdf

145. Thind, M.P.S., C.W. Tessum, I.L. Azevedo, and J.D. Marshall, 2019: Fine particulate air pollution from electricity generation in the US: Health impacts by race, income, and geography. *Environmental Science & Technology*, **53** (23), 14010–14019. https://doi.org/10.1021/acs.est.9b02527

146. Karnauskas, K.B., S.L. Miller, and A.C. Schapiro, 2020: Fossil fuel combustion is driving indoor $CO_2$ toward levels harmful to human cognition. *GeoHealth*, **4** (5), e2019GH000237. https://doi.org/10.1029/2019gh000237

147. Collins, T.W., S.E. Grineski, J. Chakraborty, and A.B. Flores, 2019: Environmental injustice and Hurricane Harvey: A household-level study of socially disparate flood exposures in Greater Houston, Texas, USA. *Environmental Research*, **179**, 108772. https://doi.org/10.1016/j.envres.2019.108772

148. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

149. Voelkel, J., D. Hellman, R. Sakuma, and V. Shandas, 2018: Assessing vulnerability to urban heat: A study of disproportionate heat exposure and access to refuge by socio-demographic status in Portland, Oregon. *International Journal of Environmental Research and Public Health*, **15** (4), 640. https://doi.org/10.3390/ijerph15040640

150. Wilhelmi, O.V., P.D. Howe, M.H. Hayden, and C.R. O'Lenick, 2021: Compounding hazards and intersecting vulnerabilities: Experiences and responses to extreme heat during COVID-19. *Environmental Research Letters*, **16** (8), 084060. https://doi.org/10.1088/1748-9326/ac1760

151. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

152. Hsu, A., G. Sheriff, T. Chakraborty, and D. Manya, 2021: Disproportionate exposure to urban heat island intensity across major US cities. *Nature Communications*, **12** (1), 2721. https://doi.org/10.1038/s41467-021-22799-5

153. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. https://doi.org/10.3390/cli8010012

154. Cong, S., D. Nock, Y.L. Qiu, and B. Xing, 2022: Unveiling hidden energy poverty using the energy equity gap. *Nature Communications*, **13** (1), 2456. https://doi.org/10.1038/s41467-022-30146-5

155. Román, M.O., E.C. Stokes, R. Shrestha, Z. Wang, L. Schultz, E.A.S. Carlo, Q. Sun, J. Bell, A. Molthan, V. Kalb, C. Ji, K.C. Seto, S.N. McClain, and M. Enenkel, 2019: Satellite-based assessment of electricity restoration efforts in Puerto Rico after Hurricane Maria. *PLoS ONE*, **14** (6), e0218883. https://doi.org/10.1371/journal.pone.0218883

156. Sotolongo, M., L. Kuhl, and S.H. Baker, 2021: Using environmental justice to inform disaster recovery: Vulnerability and electricity restoration in Puerto Rico. *Environmental Science & Policy*, **122**, 59–71. https://doi.org/10.1016/j.envsci.2021.04.004

157. Adepoju, O.E., D. Han, M. Chae, K.L. Smith, L. Gilbert, S. Choudhury, and L. Woodard, 2021: Health disparities and climate change: The intersection of three disaster events on vulnerable communities in Houston, Texas. *International Journal of Environmental Research and Public Health*, **19** (1), 35. https://doi.org/10.3390/ijerph19010035

158. Falise, A.M., I. Griffin, D. Fernandez, X. Rodriguez, E. Moore, A. Barrera, J. Suarez, L. Cutie, and G. Zhang, 2019: Carbon monoxide poisoning in Miami-Dade County following Hurricane Irma in 2017. *Disaster Medicine and Public Health Preparedness*, **13** (1), 94–96. https://doi.org/10.1017/dmp.2018.67

159. Waddell, S.L., D.T. Jayaweera, M. Mirsaeidi, J.C. Beier, and N. Kumar, 2021: Perspectives on the health effects of hurricanes: A review and challenges. *International Journal of Environmental Research and Public Health*, **18** (5), 2756. https://doi.org/10.3390/ijerph18052756

160. DOE. 2020: Low-Income Energy Affordability Data - LEAD Tool - 2018 Update. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://doi.org/10.25984/1784729

161. Drehobl, A., L. Ross, and R. Ayala, 2020: How High Are Household Energy Burdens? An Assessment of National and Metropolitan Energy Burden across the United States. American Council for an Energy-Efficient Economy, Washington, DC. https://www.aceee.org/sites/default/files/pdfs/u2006.pdf

162. Kontokosta, C.E., V.J. Reina, and B. Bonczak, 2020: Energy cost burdens for low-income and minority households. *Journal of the American Planning Association*, **86** (1), 89–105. https://doi.org/10.1080/01944363.2019.1647446

163. Ross, L., A. Drehobl, and B. Stickles, 2018: The High Cost of Energy in Rural America: Household Energy Burdens and Opportunities for Energy Efficiency. American Council for an Energy-Efficient Economy, Washington DC. https://www.aceee.org/sites/default/files/publications/researchreports/u1806.pdf

164. Jolley, G.J., C. Khalaf, G. Michaud, and A.M. Sandler, 2019: The economic, fiscal, and workforce impacts of coal-fired power plant closures in Appalachian Ohio. *Regional Science Policy & Practice*, **11** (2), 403–422. https://doi.org/10.1111/rsp3.12191

165. Wang, S.S.-C., Y. Qian, L.R. Leung, and Y. Zhang, 2021: Identifying key drivers of wildfires in the contiguous US using machine learning and game theory interpretation. *Earth's Future*, **9** (6), e2020EF001910. https://doi.org/10.1029/2020ef001910

166. Pai, S., H. Zerriffi, J. Jewell, and J. Pathak, 2020: Solar has greater techno-economic resource suitability than wind for replacing coal mining jobs. *Environmental Research Letters*, **15** (3), 034065. https://doi.org/10.1088/1748-9326/ab6c6d

167. Hansen, J.K., W.D. Jenson, A.M. Wrobel, N. Stauff, K. Biegel, T.K. Kim, R. Belles, and F. Omitaomu, 2022: Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants. INL/RPT-22-67964-Rev000. U.S. Department of Energy, Idaho National Laboratory, Idaho Falls, ID. https://doi.org/10.2172/1886660

168. Mayfield, E., J. Jenkins, E. Larson, and C. Greig, 2023: Labor pathways to achieve net-zero emissions in the United States by mid-century. *Energy Policy*, **177**, 113516. https://doi.org/10.1016/j.enpol.2023.113516

169. Pollin, R., J. Wicks-Lim, and S. Chakraborty, 2020: Ch. 3. Industrial policy employment, and just transition. In: *America's Zero Carbon Action Plan*. Sustainable Development Solutions Network, 50–104. https://irp-cdn.multiscreensite.com/6f2c9f57/files/uploaded/zero-carbon-action-plan-ch-03.pdf

170. Wei, M., S. Patadia, and D.M. Kammen, 2010: Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, **38** (2), 919–931. https://doi.org/10.1016/j.enpol.2009.10.044

171. Raimi, D., S. Carley, and D. Konisky, 2022: Mapping county-level vulnerability to the energy transition in US fossil fuel communities. *Scientific Reports*, **12** (1), 15748. https://doi.org/10.1038/s41598-022-19927-6

172. Righetti, T.K., T. Stoellinger, and R. Godby, 2021: Adapting to coal plant closures: A framework to understand state energy transition resistance. *Environmental Law*, **51** (4), 957–990. https://doi.org/10.13140/rg.2.2.32801.74083

173. Craig, M.T., P. Jaramillo, B.-M. Hodge, B. Nijssen, and C. Brancucci, 2020: Compounding climate change impacts during high stress periods for a high wind and solar power system in Texas. *Environmental Research Letters*, **15** (2), 024002. https://doi.org/10.1088/1748-9326/ab6615

174. AghaKouchak, A., F. Chiang, L.S. Huning, C.A. Love, I. Mallakpour, O. Mazdiyasni, H. Moftakhari, S.M. Papalexiou, E. Ragno, and M. Sadegh, 2020: Climate extremes and compound hazards in a warming world. *Annual Review of Earth and Planetary Sciences*, **48** (1), 519–548. https://doi.org/10.1146/annurev-earth-071719-055228

175. Zscheischler, J., S. Westra, B.J.J.M. van den Hurk, S.I. Seneviratne, P.J. Ward, A. Pitman, A. AghaKouchak, D.N. Bresch, M. Leonard, T. Wahl, and X. Zhang, 2018: Future climate risk from compound events. *Nature Climate Change*, **8** (6), 469–477. https://doi.org/10.1038/s41558-018-0156-3

176. Wells, E.M., M. Boden, I. Tseytlin, and I. Linkov, 2022: Modeling critical infrastructure resilience under compounding threats: A systematic literature review. *Progress in Disaster Science*, **15**, 100244. https://doi.org/10.1016/j.pdisas.2022.100244

177. Mahzarnia, M., M.P. Moghaddam, P.T. Baboli, and P. Siano, 2020: A review of the measures to enhance power systems resilience. *IEEE Systems Journal*, **14** (3), 4059–4070. https://doi.org/10.1109/jsyst.2020.2965993

178. Ratnam, E.L., K.G.H. Baldwin, P. Mancarella, M. Howden, and L. Seebeck, 2020: Electricity system resilience in a world of increased climate change and cybersecurity risk. *The Electricity Journal*, **33** (9), 106833. https://doi.org/10.1016/j.tej.2020.106833

179. Bommareddy, S., B. Gilby, M. Khan, I. Chiu, M. Panteli, J.W. van de Lindt, L. Wells, Y. Amir, and A. Babay, 2022: Data-centric analysis of compound threats to critical infrastructure control systems. In: *52nd Annual IEEE/IFIP International Conference on Dependable Systems and Networks Workshops* (DSN-W). IEEE, 72–79. https://doi.org/10.1109/DSN-W54100.2022.00022

180. Paul, S., F. Ding, K. Utkarsh, W. Liu, M.J. O'Malley, and J. Barnett, 2022: On vulnerability and resilience of cyber-physical power systems: A review. *IEEE Systems Journal*, **16** (2), 2367–2378. https://doi.org/10.1109/jsyst.2021.3123904

181. Moftakhari, H. and A. AghaKouchak, 2019: Increasing exposure of energy infrastructure to compound hazards: Cascading wildfires and extreme rainfall. *Environmental Research Letters*, **14** (10), 104018. https://doi.org/10.1088/1748-9326/ab41a6

182. Hill, J., J. Kern, D.E. Rupp, N. Voisin, and G. Characklis, 2021: The effects of climate change on interregional electricity market dynamics on the U.S. West Coast. *Earth's Future*, **9** (12), e2021EF002400. https://doi.org/10.1029/2021ef002400

183. Zhang, W. and G. Villarini, 2020: Deadly compound heat stress-flooding hazard across the central United States. *Geophysical Research Letters*, **47** (15), e2020GL089185. https://doi.org/10.1029/2020gl089185

184. EIA, 2021: Today in Energy: Extreme Winter Weather Is Disrupting Energy Supply and Demand, Particularly in Texas. U.S. Energy Information Administration, Washington, DC, accessed February 19, 2021. https://www.eia.gov/todayinenergy/detail.php?id=46836

185. FERC, 2021: FERC, NERC and Regional Entity Staff Report: The February 2021 Cold Weather Outages in Texas and the South Central United States. Federal Energy Regulatory Commission, North American Electric Reliability Corporation. https://www.naesb.org/pdf4/ferc_nerc_regional_entity_staff_report_feb2021_cold_weather_outages_111621.pdf

186. Moreno, R., D.N. Trakas, M. Jamieson, M. Panteli, P. Mancarella, G. Strbac, C. Marnay, and N. Hatziargyriou, 2022: Microgrids against wildfires: Distributed energy resources enhance system resilience. *IEEE Power and Energy Magazine*, **20** (1), 78–89. https://doi.org/10.1109/mpe.2021.3122772

187. Vazquez, D.A.Z., F. Qiu, N. Fan, and K. Sharp, 2022: Wildfire mitigation plans in power systems: A literature review. *IEEE Transactions on Power Systems*, **37** (5), 3540–3551. https://doi.org/10.1109/tpwrs.2022.3142086

188. Taylor, W.O., P.L. Watson, D. Cerrai, and E.N. Anagnostou, 2022: Dynamic modeling of the effects of vegetation management on weather-related power outages. *Electric Power Systems Research*, **207**, 107840. https://doi.org/10.1016/j.epsr.2022.107840

189. Perera, A.T.D., B. Zhao, Z. Wang, K. Soga, and T. Hong, 2023: Optimal design of microgrids to improve wildfire resilience for vulnerable communities at the wildland-urban interface. *Applied Energy*, **335**, 120744. https://doi.org/10.1016/j.apenergy.2023.120744

190. Gong, H. and D.M. Ionel, 2021: Improving the power outage resilience of buildings with solar PV through the use of battery systems and EV energy storage. *Energies*, **14** (18). https://doi.org/10.3390/en14185749

191. Katopodis, T. and A. Sfetsos, 2019: A review of climate change impacts to oil sector critical services and suggested recommendations for industry uptake. *Infrastructures*, **4** (4), 74. https://doi.org/10.3390/infrastructures4040074

192. Gerlak, A.K., J. Weston, B. McMahan, R.L. Murray, and M. Mills-Novoa, 2018: Climate risk management and the electricity sector. *Climate Risk Management*, **19**, 12–22. https://doi.org/10.1016/j.crm.2017.12.003

193. Jordan, D., T. Barnes, N. Haegel, and I. Repins, 2021: Build solar-energy systems to last—Save billions. *Nature*, **600** (7888), 215–217. https://doi.org/10.1038/d41586-021-03626-9

194. Zamuda, C.D., T. Wall, L. Guzowski, J. Bergerson, J. Ford, L.P. Lewis, R. Jeffers, and S. DeRosa, 2019: Resilience management practices for electric utilities and extreme weather. *The Electricity Journal*, **32** (9), 106642. https://doi.org/10.1016/j.tej.2019.106642

195. Caldwell, P.M., C.R. Terai, B. Hillman, N.D. Keen, P. Bogenschutz, W. Lin, H. Beydoun, M. Taylor, L. Bertagna, A.M. Bradley, T.C. Clevenger, A.S. Donahue, C. Eldred, J. Foucar, J.-C. Golaz, O. Guba, R. Jacob, J. Johnson, J. Krishna, W. Liu, K. Pressel, A.G. Salinger, B. Singh, A. Steyer, P. Ullrich, D. Wu, X. Yuan, J. Shpund, H.-Y. Ma, and C.S. Zender, 2021: Convection-permitting simulations with the E3SM global atmosphere model. *Journal of Advances in Modeling Earth Systems*, **13** (11), e2021MS002544. https://doi.org/10.1029/2021ms002544

196. Leung, L.R., D.C. Bader, M.A. Taylor, and R.B. McCoy, 2020: An introduction to the E3SM special collection: Goals, science drivers, development, and analysis. *Journal of Advances in Modeling Earth Systems*, **12** (11), e2019MS001821. https://doi.org/10.1029/2019ms001821

197. Mauree, D., E. Naboni, S. Coccolo, A.T.D. Perera, V.M. Nik, and J.-L. Scartezzini, 2019: A review of assessment methods for the urban environment and its energy sustainability to guarantee climate adaptation of future cities. *Renewable and Sustainable Energy Reviews*, **112**, 733–746. https://doi.org/10.1016/j.rser.2019.06.005

198. McGuire, M., S. Gangopadhyay, J. Martin, G.T. Pederson, C.A. Woodhouse, and J.S. Littell, 2021: Water Reliability in the West—Secure Water Act Section 9503(C). Technical Memorandum No. ENV-2021-001. U.S. Bureau of Reclamation, 60 pp. http://pubs.er.usgs.gov/publication/70219467

199. Balaguru, K., D.R. Judi, and L.R. Leung, 2016: Future hurricane storm surge risk for the U.S. gulf and Florida coasts based on projections of thermodynamic potential intensity. *Climatic Change*, **138** (1), 99–110. https://doi.org/10.1007/s10584-016-1728-8

200. Sippel, S., N. Meinshausen, E. Székely, E. Fischer, A.G. Pendergrass, F. Lehner, and R. Knutti, 2021: Robust detection of forced warming in the presence of potentially large climate variability. *Science Advances*, **7** (43), 4429. https://doi.org/10.1126/sciadv.abh4429

201. Tebaldi, C., R. Ranasinghe, M. Vousdoukas, D.J. Rasmussen, B. Vega-Westhoff, E. Kirezci, R.E. Kopp, R. Sriver, and L. Mentaschi, 2021: Extreme sea levels at different global warming levels. *Nature Climate Change*, **11** (9), 746–751. https://doi.org/10.1038/s41558-021-01127-1

202. Wang, J., W. Zuo, L. Rhode-Barbarigos, X. Lu, J. Wang, and Y. Lin, 2019: Literature review on modeling and simulation of energy infrastructures from a resilience perspective. *Reliability Engineering & System Safety*, **183**, 360–373. https://doi.org/10.1016/j.ress.2018.11.029

203. Beswick, R.R., A.M. Oliveira, and Y. Yan, 2021: Does the green hydrogen economy have a water problem? *ACS Energy Letters*, **6** (9), 3167–3169. https://doi.org/10.1021/acsenergylett.1c01375

204. Watson, E.B. and A.H. Etemadi, 2020: Modeling electrical grid resilience under hurricane wind conditions with increased solar and wind power generation. *IEEE Transactions on Power Systems*, **35** (2), 929–937. https://doi.org/10.1109/tpwrs.2019.2942279

205. Cohen, S.M., A. Dyreson, S. Turner, V. Tidwell, N. Voisin, and A. Miara, 2022: A multi-model framework for assessing long- and short-term climate influences on the electric grid. *Applied Energy*, **317**, 119193. https://doi.org/10.1016/j.apenergy.2022.119193

206. Miara, A., S.M. Cohen, J. Macknick, C.J. Vörösmarty, F. Corsi, Y. Sun, V.C. Tidwell, R. Newmark, and B.M. Fekete, 2019: Climate-water adaptation for future US electricity infrastructure. *Environmental Science & Technology*, **53** (23), 14029–14040. https://doi.org/10.1021/acs.est.9b03037

207. Ralston Fonseca, F., M. Craig, P. Jaramillo, M. Bergés, E. Severnini, A. Loew, H. Zhai, Y. Cheng, B. Nijssen, N. Voisin, and J. Yearsley, 2021: Effects of climate change on capacity expansion decisions of an electricity generation fleet in the southeast U.S. *Environmental Science & Technology*, **55** (4), 2522–2531. https://doi.org/10.1021/acs.est.0c06547

208. Wessel, J., J.D. Kern, N. Voisin, K. Oikonomou, and J. Haas, 2022: Technology pathways could help drive the U.S. West Coast grid's exposure to hydrometeorological uncertainty. *Earth's Future*, **10** (1), e2021EF002187. https://doi.org/10.1029/2021ef002187

209. Levi, P.J., S.D. Kurland, M. Carbajales-Dale, J.P. Weyant, A.R. Brandt, and S.M. Benson, 2019: Macro-energy systems: Toward a new discipline. *Joule*, **3** (10), 2282–2286. https://doi.org/10.1016/j.joule.2019.07.017

210. Reed, P.M., A. Hadjimichael, R.H. Moss, E. Monier, S. Alba, C. Brelsford, C. Burleyson, S. Cohen, A. Dyreson, D. Gold, R. Gupta, K. Keller, M. Konar, J. Macknick, J. Morris, V. Srikrishnan, N. Voisin, and J. Yoon, 2022: MultiSector Dynamics: Scientific Challenges and a Research Vision for 2030. U.S. Department of Energy, Office of Science. https://doi.org/10.5281/zenodo.6144309

211. Szinai, J.K., R. Deshmukh, D.M. Kammen, and A.D. Jones, 2020: Evaluating cross-sectoral impacts of climate change and adaptations on the energy-water nexus: A framework and California case study. *Environmental Research Letters*, **15** (12), 124065. https://doi.org/10.1088/1748-9326/abc378

212. Voisin, N., V. Tidwell, M. Kintner-Meyer, and F. Boltz, 2019: Planning for sustained water-electricity resilience over the U.S.: Persistence of current water-electricity operations and long-term transformative plans. *Water Security*, **7**, 100035. https://doi.org/10.1016/j.wasec.2019.100035

213. Yoon, J., P. Romero-Lankao, Y.C.E. Yang, C. Klassert, N. Urban, K. Kaiser, K. Keller, B. Yarlagadda, N. Voisin, P.M. Reed, and R. Moss, 2022: A typology for characterizing human action in multisector dynamics models. *Earth's Future*, **10** (8), e2021EF002641. https://doi.org/10.1029/2021ef002641

214. Bennett, J.A., C.N. Trevisan, J.F. DeCarolis, C. Ortiz-García, M. Pérez-Lugo, B.T. Etienne, and A.F. Clarens, 2021: Extending energy system modelling to include extreme weather risks and application to hurricane events in Puerto Rico. *Nature Energy*, **6** (3), 240–249. https://doi.org/10.1038/s41560-020-00758-6

215. Ross, R., V. Pillitteri, R. Graubart, D. Bodeau, and R. McQuaid, 2021: Developing Cyber-Resilient Systems: A Systems Security Engineering Approach. NIST Special Publication, SP 800-160 Vol. 2 Rev. 1. U.S. Department of Commerce, National Institute of Standards and Technology. https://doi.org/10.6028/nist.sp.800-160v2r1

216. Tsvetanov, T. and S. Slaria, 2021: The effect of the Colonial Pipeline shutdown on gasoline prices. *Economics Letters*, **209**, 110122. https://doi.org/10.1016/j.econlet.2021.110122

217. AghaKouchak, A., L.S. Huning, F. Chiang, M. Sadegh, F. Vahedifard, O. Mazdiyasni, H. Moftakhari, and I. Mallakpour, 2018: How do natural hazards cascade to cause disasters? *Nature*, **561** (7724), 458–460. https://doi.org/10.1038/d41586-018-06783-6

218. Osman, A.I., L. Chen, M. Yang, G. Msigwa, M. Farghali, S. Fawzy, D.W. Rooney, and P.-S. Yap, 2023: Cost, environmental impact, and resilience of renewable energy under a changing climate: A review. *Environmental Chemistry Letters*, **21** (2), 741–764. https://doi.org/10.1007/s10311-022-01532-8

219. Dyreson, A., N. Devineni, S.W.D. Turner, T. De Silva M, A. Miara, N. Voisin, S. Cohen, and J. Macknick, 2022: The role of regional connections in planning for future power system operations under climate extremes. *Earth's Future*, **10** (6), e2021EF002554. https://doi.org/10.1029/2021ef002554

220. EIA, 2021: Today in Energy: U.S. Electric Power Sector's Use of Water Continued Its Downward Trend in 2020. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/todayinenergy/detail.php?id=50698

221. Bushnaq, O.M., A. Chaaban, and T.Y. Al-Naffouri, 2021: The role of UAV-IoT networks in future wildfire detection. *IEEE Internet of Things Journal*, **8** (23), 16984–16999. https://doi.org/10.1109/jiot.2021.3077593

222. OCM, 2022: Digital Coasts. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. https://coast.noaa.gov/digitalcoast/

223. U.S. Federal Government, 2021: U.S. Climate Resilience Toolkit: Energy [Webpage]. https://toolkit.climate.gov/topics/energy-supply-and-use

224. GAO, 2019: Climate Resilience: A Strategic Investment Approach for High-Priority Projects Could Help Target Federal Resources. GAO-20-127. U.S. Government Accountability Office. https://www.gao.gov/products/gao-20-127

225. Hong, T., Z. Wang, X. Luo, and W. Zhang, 2020: State-of-the-art on research and applications of machine learning in the building life cycle. *Energy and Buildings*, **212**, 109831. https://doi.org/10.1016/j.enbuild.2020.109831

226. Kumbhar, A., P.G. Dhawale, S. Kumbhar, U. Patil, and P. Magdum, 2021: A comprehensive review: Machine learning and its application in integrated power system. *Energy Reports*, **7**, 5467–5474. https://doi.org/10.1016/j.egyr.2021.08.133

227. Satchwell, A., M.A. Piette, A. Khandekar, J. Granderson, N.M. Frick, R. Hledik, A. Faruqui, L. Lam, S. Ross, J. Cohen, K. Wang, D. Urigwe, D. Delurey, M. Neukomm, and D. Nemtzow, 2021: A National Roadmap for Grid-Interactive Efficient Buildings. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://gebroadmap.lbl.gov/

228. Drgoňa, J., J. Arroyo, I. Cupeiro Figueroa, D. Blum, K. Arendt, D. Kim, E.P. Ollé, J. Oravec, M. Wetter, D.L. Vrabie, and L. Helsen, 2020: All you need to know about model predictive control for buildings. *Annual Reviews in Control*, **50**, 190–232. https://doi.org/10.1016/j.arcontrol.2020.09.001

229. Wang, Z. and T. Hong, 2020: Reinforcement learning for building controls: The opportunities and challenges. *Applied Energy*, **269**, 115036. https://doi.org/10.1016/j.apenergy.2020.115036

230. Nubbe, V. and M. Yamada, 2019: Grid-Interactve Efficient Buildings Technical Report Series: Lighting and Electronics. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://doi.org/10.2172/1580213

231. Bistline, J.E.T., 2021: Roadmaps to net-zero emissions systems: Emerging insights and modeling challenges. *Joule*, **5** (10), 2551–2563. https://doi.org/10.1016/j.joule.2021.09.012

232. IEA, 2021: Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency, Paris, France. https://www.iea.org/reports/net-zero-by-2050

233. IPCC, 2023: Summary for policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Lee, H. and J. Romero, Eds. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 1-34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

234. Murphy, C., T. Mai, Y. Sun, P. Jadun, P. Donohoo-Vallett, M. Muratori, R. Jones, and B. Nelson, 2020: High electrification futures: Impacts to the U.S. bulk power system. *The Electricity Journal*, **33** (10), 106878. https://doi.org/10.1016/j.tej.2020.106878

235. McLaughlin, K. and L. Bird, 2021: The US Set a Record for Renewables in 2020, but More Is Needed. World Resources Institute. https://www.wri.org/insights/renewable-energy-2020-record-us

236. EIA, 2022: Annual Energy Outlook 2022. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/outlooks/aeo/narrative/introduction/sub-topic-02.php

237. DOS and EOP, 2021: The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. U.S. Department of State and U.S. Executive Office of the President, Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2021/10/us-long-term-strategy.pdf

238. Larson, E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, E. Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan, 2021: Final Report Summary—Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Princeton University, Princeton, NJ. https://netzeroamerica.princeton.edu/the-report

239. Mueller, J.T. and M.M. Brooks, 2020: Burdened by renewable energy? A multi-scalar analysis of distributional justice and wind energy in the United States. *Energy Research & Social Science*, **63**, 101406. https://doi.org/10.1016/j.erss.2019.101406

240. FCAB, 2021: National Blueprint for Lithium Batteries 2021–2030. Federal Consortium for Advanced Batteries. https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf

241. DOE, 2021: Hydrogen Shot. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/eere/fuelcells/hydrogen-shot

242. NRC, 2021: Application Review Schedule for the NuScale US600 Design. U.S. Nuclear Regulatory Commission. https://www.nrc.gov/reactors/new-reactors/smr/nuscale/review-schedule.html

243. Carley, S. and D.M. Konisky, 2020: The justice and equity implications of the clean energy transition. *Nature Energy*, **5** (8), 569–577. https://doi.org/10.1038/s41560-020-0641-6

244. McNamara, W., H. Passell, M. Montes, R. Jeffers, and I. Gyuk, 2022: Seeking energy equity through energy storage. *The Electricity Journal*, **35** (1), 107063. https://doi.org/10.1016/j.tej.2021.107063

245. Widerynski, S., P. Schramm, K. Conlon, R. Noe, E. Grossman, M. Hawkins, S. Nayak, M. Roach, and A.S. Hilts, 2017: The Use of Cooling Centers to Prevent Heat-Related Illness: Summary of Evidence and Strategies for Implementation. Centers for Disease Control and Prevention, National Center for Environmental Health. https://www.cdc.gov/climateandhealth/docs/useofcoolingcenters.pdf

246. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

247. Gallagher, C.L. and T. Holloway, 2020: Integrating air quality and public health benefits in U.S. decarbonization strategies. *Frontiers in Public Health*, **8**, 563358. https://doi.org/10.3389/fpubh.2020.563358

248. Markandya, A., J. Sampedro, S.J. Smith, R. Van Dingenen, C. Pizarro-Irizar, I. Arto, and M. González-Eguino, 2018: Health co-benefits from air pollution and mitigation costs of the Paris Agreement: A modelling study. *The Lancet Planetary Health*, **2** (3), e126–e133. https://doi.org/10.1016/s2542-5196(18)30029-9

249. Shindell, D., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8** (4), 291–295. https://doi.org/10.1038/s41558-018-0108-y

250. Vandyck, T., K. Keramidas, A. Kitous, J.V. Spadaro, R. Van Dingenen, M. Holland, and B. Saveyn, 2018: Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nature Communications*, **9** (1), 4939. https://doi.org/10.1038/s41467-018-06885-9

251. Carpenter, A. and M. Wagner, 2019: Environmental justice in the oil refinery industry: A panel analysis across United States counties. *Ecological Economics*, **159**, 101–109. https://doi.org/10.1016/j.ecolecon.2019.01.020

252. Elliott, M. and N. Kittner, 2022: Operational grid and environmental impacts for a V2G-enabled electric school bus fleet using DC fast chargers. *Sustainable Production and Consumption*, **30**, 316–330. https://doi.org/10.1016/j.spc.2021.11.029

253. Rowangould, G.M., 2013: A census of the US near-roadway population: Public health and environmental justice considerations. *Transportation Research Part D: Transport and Environment*, **25**, 59–67. https://doi.org/10.1016/j.trd.2013.08.003

254. Babaee, S., D.H. Loughlin, and P.O. Kaplan, 2020: Incorporating upstream emissions into electric sector nitrogen oxide reduction targets. *Cleaner Engineering and Technology*, **1**, 100017. https://doi.org/10.1016/j.clet.2020.100017

255. Gonzalez-Salazar, M.A., T. Kirsten, and L. Prchlik, 2018: Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. *Renewable and Sustainable Energy Reviews*, **82** (1), 1497–1513. https://doi.org/10.1016/j.rser.2017.05.278

256. Luderer, G., M. Pehl, A. Arvesen, T. Gibon, B.L. Bodirsky, H.S. de Boer, O. Fricko, M. Hejazi, F. Humpenöder, G. Iyer, S. Mima, I. Mouratiadou, R.C. Pietzcker, A. Popp, M. van den Berg, D. van Vuuren, and E.G. Hertwich, 2019: Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Communications*, **10** (1), 5229. https://doi.org/10.1038/s41467-019-13067-8

257. Ou, Y., W. Shi, S.J. Smith, C.M. Ledna, J.J. West, C.G. Nolte, and D.H. Loughlin, 2018: Estimating environmental co-benefits of U.S. low-carbon pathways using an integrated assessment model with state-level resolution. *Applied Energy*, **216**, 482–493. https://doi.org/10.1016/j.apenergy.2018.02.122

258. Brown, M.A., A. Soni, M.V. Lapsa, K. Southworth, and M. Cox, 2020: High energy burden and low-income energy affordability: Conclusions from a literature review. *Progress in Energy*, **2** (4), 042003. https://doi.org/10.1088/2516-1083/abb954

259. Zamuda, C.D. and A. Ressler, 2020: Federal adaptation and mitigation programs supporting community investment in electricity resilience to extreme weather. *The Electricity Journal*, **33** (8), 106825. https://doi.org/10.1016/j.tej.2020.106825

260. DOE, 2021: Weatherization Assistance Program Fact Sheet. U.S. Department of Energy, 2 pp. https://www.energy.gov/sites/default/files/2021/01/f82/WAP-fact-sheet_2021_0.pdf

261. DOE, 2021: Equity in Energy: An Energy Economy for Everyone. U.S. Department of Energy, Office of Economic Impact and Diversity. https://www.energy.gov/sites/default/files/2021/01/f82/Equity_in_Energy_Booklet_1_11.pdf

262. Zeng, Z., A.D. Ziegler, T. Searchinger, L. Yang, A. Chen, K. Ju, S. Piao, L.Z.X. Li, P. Ciais, D. Chen, J. Liu, C. Azorin-Molina, A. Chappell, D. Medvigy, and E.F. Wood, 2019: A reversal in global terrestrial stilling and its implications for wind energy production. *Nature Climate Change*, **9** (12), 979–985. https://doi.org/10.1038/s41558-019-0622-6

263. Pryor, S.C., J.J. Coburn, R.J. Barthelmie, and T.J. Shepherd, 2023: Projecting future energy production from operating wind farms in North America. Part I: Dynamical downscaling. *Journal of Applied Meteorology and Climatology*, **62** (1), 63–80. https://doi.org/10.1175/jamc-d-22-0044.1

264. Yalew, S.G., M.T.H. van Vliet, D.E.H.J. Gernaat, F. Ludwig, A. Miara, C. Park, E. Byers, E. De Cian, F. Piontek, G. Iyer, I. Mouratiadou, J. Glynn, M. Hejazi, O. Dessens, P. Rochedo, R. Pietzcker, R. Schaeffer, S. Fujimori, S. Dasgupta, S. Mima, S.R.S. da Silva, V. Chaturvedi, R. Vautard, and D.P. van Vuuren, 2020: Impacts of climate change on energy systems in global and regional scenarios. *Nature Energy*, **5** (10), 794–802. https://doi.org/10.1038/s41560-020-0664-z

265. Burleyson, C.D., G. Iyer, M. Hejazi, S. Kim, P. Kyle, J.S. Rice, A.D. Smith, Z.T. Taylor, N. Voisin, and Y. Xie, 2020: Future western U.S. building electricity consumption in response to climate and population drivers: A comparative study of the impact of model structure. *Energy*, **208**, 118312. https://doi.org/10.1016/j.energy.2020.118312

266. Marsooli, R., N. Lin, K. Emanuel, and K. Feng, 2019: Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. *Nature Communications*, **10** (1), 3785. https://doi.org/10.1038/s41467-019-11755-z

267. Cohen, J., K. Pfeiffer, and J.A. Francis, 2018: Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States. *Nature Communications*, **9** (1), 869. https://doi.org/10.1038/s41467-018-02992-9

268. Blackport, R., J.A. Screen, K. van der Wiel, and R. Bintanja, 2019: Minimal influence of reduced Arctic sea ice on coincident cold winters in mid-latitudes. *Nature Climate Change*, **9** (9), 697–704. https://doi.org/10.1038/s41558-019-0551-4

269. Cohen, J., X. Zhang, J. Francis, T. Jung, R. Kwok, J. Overland, T.J. Ballinger, U.S. Bhatt, H.W. Chen, D. Coumou, S. Feldstein, H. Gu, D. Handorf, G. Henderson, M. Ionita, M. Kretschmer, F. Laliberte, S. Lee, H.W. Linderholm, W. Maslowski, Y. Peings, K. Pfeiffer, I. Rigor, T. Semmler, J. Stroeve, P.C. Taylor, S. Vavrus, T. Vihma, S. Wang, M. Wendisch, Y. Wu, and J. Yoon, 2020: Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather. *Nature Climate Change*, **10** (1), 20–29. https://doi.org/10.1038/s41558-019-0662-y

270. Tian, Q., G. Huang, K. Hu, and D. Niyogi, 2019: Observed and global climate model based changes in wind power potential over the Northern Hemisphere during 1979–2016. *Energy*, **167**, 1224–1235. https://doi.org/10.1016/j.energy.2018.11.027

271. Craig, M.T., S. Cohen, J. Macknick, C. Draxl, O.J. Guerra, M. Sengupta, S.E. Haupt, B.M. Hodge, and C. Brancucci, 2018: A review of the potential impacts of climate change on bulk power system planning and operations in the United States. *Renewable and Sustainable Energy Reviews*, **98**, 255–267. https://doi.org/10.1016/j.rser.2018.09.022

272. Cronin, J., G. Anandarajah, and O. Dessens, 2018: Climate change impacts on the energy system: A review of trends and gaps. *Climatic Change*, **151** (2), 79–93. https://doi.org/10.1007/s10584-018-2265-4

273. Auffhammer, M., P. Baylis, and C.H. Hausman, 2017: Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (8), 1886–1891. https://doi.org/10.1073/pnas.1613193114

274. Martel, J.L., F.P. Brissette, P. Lucas-Picher, M. Troin, and R. Arsenault, 2021: Climate change and rainfall intensity–duration–frequency curves: Overview of science and guidelines for adaptation. *Journal of Hydrologic Engineering*, **26** (10), 03121001. https://doi.org/10.1061/(asce)he.1943-5584.0002122

275. Maxim, A. and E. Grubert, 2022: Anticipating climate-related changes to residential energy burden in the United States: Advance planning for equity and resilience. *Environmental Justice*, **15** (3), 139–148. https://doi.org/10.1089/env.2021.0056

276. Leon, W. and A. Ziai, 2023: Table of 100% Clean Energy States. Clean Energy Group, accessed April 5, 2023. https://www.cesa.org/projects/100-clean-energy-collaborative/guide/table-of-100-clean-energy-states/

277. McMahan, B. and A.K. Gerlak, 2020: Climate risk assessment and cascading impacts: Risks and opportunities for an electrical utility in the U.S. Southwest. *Climate Risk Management*, **29**, 100240. https://doi.org/10.1016/j.crm.2020.100240

278. EPA, 2022: State Energy and Environment Guide to Action: Electricity Resources Planning and Procurement. EPA-430-R-22-004. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-08/Electricity%20Resource%20Planning%20and%20Procurement_508.pdf

279. Cooke, A., J.S. Homer, J. Lessick, D. Bhatnagar, and K. Kazimierczuk, 2021: A Review of Water and Climate Change Analysis in Electric Utility Integrated Resource Planning. PNNL-30910. U.S. Department of Energy, Pacific Northwest National Laboratory. https://doi.org/10.2172/1906361

280. Deser, C., A. Phillips, V. Bourdette, and H. Teng, 2012: Uncertainty in climate change projections: The role of internal variability. *Climate Dynamics*, **38** (3), 527–546. https://doi.org/10.1007/s00382-010-0977-x

281. Golaz, J.-C., L.P. Van Roekel, X. Zheng, A.F. Roberts, J.D. Wolfe, W. Lin, A.M. Bradley, Q. Tang, M.E. Maltrud, R.M. Forsyth, C. Zhang, T. Zhou, K. Zhang, C.S. Zender, M. Wu, H. Wang, A.K. Turner, B. Singh, J.H. Richter, Y. Qin, M.R. Petersen, A. Mametjanov, P.-L. Ma, V.E. Larson, J. Krishna, N.D. Keen, N. Jeffery, E.C. Hunke, W.M. Hannah, O. Guba, B.M. Griffin, Y. Feng, D. Engwirda, A.V. Di Vittorio, C. Dang, L.M. Conlon, C.-C.-J. Chen, M.A. Brunke, G. Bisht, J.J. Benedict, X.S. Asay-Davis, Y. Zhang, M. Zhang, X. Zeng, S. Xie, P.J. Wolfram, T. Vo, M. Veneziani, T.K. Tesfa, S. Sreepathi, A.G. Salinger, J.E.J. Reeves Eyre, M.J. Prather, S. Mahajan, Q. Li, P.W. Jones, R.L. Jacob, G.W. Huebler, X. Huang, B.R. Hillman, B.E. Harrop, J.G. Foucar, Y. Fang, D.S. Comeau, P.M. Caldwell, T. Bartoletti, K. Balaguru, M.A. Taylor, R.B. McCoy, L.R. Leung, and D.C. Bader, 2022: The DOE E3SM Model Version 2: Overview of the physical model and initial model evaluation. *Journal of Advances in Modeling Earth Systems*, **14** (12), e2022MS003156. https://doi.org/10.1029/2022ms003156

282. Kay, J.E., C. Deser, A. Phillips, A. Mai, C. Hannay, G. Strand, J.M. Arblaster, S.C. Bates, G. Danabasoglu, J. Edwards, M. Holland, P. Kushner, J.F. Lamarque, D. Lawrence, K. Lindsay, A. Middleton, E. Munoz, R. Neale, K. Oleson, L. Polvani, and M. Vertenstein, 2015: The Community Earth System Model (CESM) large ensemble Project: A community resource for studying climate change in the presence of internal climate variability. *Bulletin of the American Meteorological Society*, **96** (8), 1333–1349. https://doi.org/10.1175/bams-d-13-00255.1

283. Maher, N., S. Milinski, and R. Ludwig, 2021: Large ensemble climate model simulations: Introduction, overview, and future prospects for utilising multiple types of large ensemble. *Earth System Dynamics*, **12** (2), 401–418. https://doi.org/10.5194/esd-12-401-2021

284. Peng, W., G. Iyer, V. Bosetti, V. Chaturvedi, J. Edmonds, A.A. Fawcett, S. Hallegatte, D.G. Victor, D. van Vuuren, and J. Weyant, 2021: Climate policy models need to get real about people—Here's how. *Nature*, **594** (7862), 174–176. https://doi.org/10.1038/d41586-021-01500-2

285. Wise, M., P. Patel, Z. Khan, S.H. Kim, M. Hejazi, and G. Iyer, 2019: Representing power sector detail and flexibility in a multi-sector model. *Energy Strategy Reviews*, **26**, 100411. https://doi.org/10.1016/j.esr.2019.100411

286. IEA, 2021: About CCUS. International Energy Agency, accessed April 2021. https://www.iea.org/reports/about-ccus

287. IEA, 2021: Direct Air Capture: More Efforts Needed. International Energy Agency, Paris, France. https://www.iea.org/reports/direct-air-capture

288. Gohlke, D., Y. Zhou, X. Wu, and C. Courtney, 2022: Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010–2021. ANL-22/71. U.S. Department of Energy, Argonne National Laboratory. https://doi.org/10.2172/1898424

289. National Academies of Sciences, Engineering, and Medicine, 2020: *Models to Inform Planning for the Future of Electric Power in the United States: Proceedings of a Workshop*. The National Academies Press, Washington, DC, 88 pp. https://doi.org/10.17226/25880

290. Tang, Q., S.A. Klein, S. Xie, W. Lin, J.C. Golaz, E.L. Roesler, M.A. Taylor, P.J. Rasch, D.C. Bader, L.K. Berg, P. Caldwell, S.E. Giangrande, R.B. Neale, Y. Qian, L.D. Riihimaki, C.S. Zender, Y. Zhang, and X. Zheng, 2019: Regionally refined test bed in E3SM atmosphere model version 1 (EAMv1) and applications for high-resolution modeling. *Geoscientific Model Development*, **12** (7), 2679–2706. https://doi.org/10.5194/gmd-12-2679-2019

291. Macknick, J., A. Kandt, P. Kurup, X. Li, J. McCall, A. Miara, J. Sperling, and A. de Fontaine, 2019: Water Security Grand Challenge Workshop Outcomes. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/eere/analysis/articles/water-security-grand-challenge-workshop-outcomes

292. Mouratiadou, I., M. Bevione, D.L. Bijl, L. Drouet, M. Hejazi, S. Mima, M. Pehl, and G. Luderer, 2018: Water demand for electricity in deep decarbonisation scenarios: A multi-model assessment. *Climatic Change*, **147** (1), 91–106. https://doi.org/10.1007/s10584-017-2117-7

293. Hadjimichael, A., J. Quinn, E. Wilson, P. Reed, L. Basdekas, D. Yates, and M. Garrison, 2020: Defining robustness, vulnerabilities, and consequential scenarios for diverse stakeholder interests in institutionally complex river basins. *Earth's Future*, **8** (7), e2020EF001503. https://doi.org/10.1029/2020ef001503

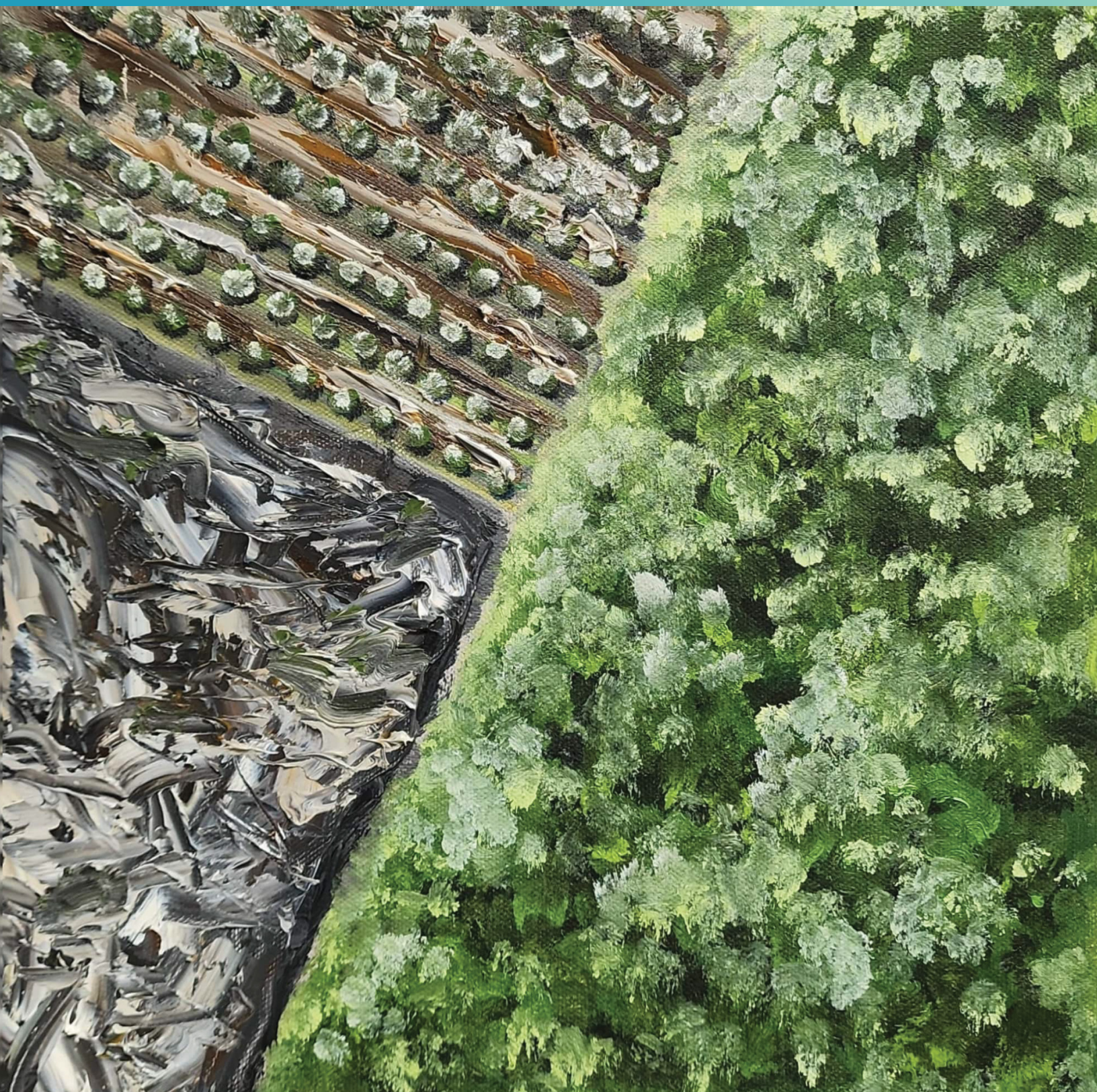
294. Shindell, D., M. Ru, Y. Zhang, K. Seltzer, G. Faluvegi, L. Nazarenko, G.A. Schmidt, L. Parsons, A. Challapalli, L. Yang, and A. Glick, 2021: Temporal and spatial distribution of health, labor, and crop benefits of climate change mitigation in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (46), e2104061118. https://doi.org/10.1073/pnas.2104061118

295. Oke, D., J.B. Dunn, and T.R. Hawkins, 2022: The contribution of biomass and waste resources to decarbonizing transportation and related energy and environmental effects. *Sustainable Energy & Fuels*, **6** (3), 721–735. https://doi.org/10.1039/d1se01742j

296. Lamers, P., T. Ghosh, S. Upasani, R. Sacchi, and V. Daioglou, 2023: Linking life cycle and integrated assessment modeling to evaluate technologies in an evolving system context: A power-to-hydrogen case study for the United States. *Environmental Science & Technology*, **57** (6), 2464–2473. https://doi.org/10.1021/acs.est.2c04246

Fifth National Climate Assessment: Chapter 6

# Land Cover and Land-Use Change



## Dedication

We dedicate this chapter to the memory of our friend and colleague Brad Reed. Brad served as a coordinating lead author for the Land Cover and Land-Use Change chapter before he suddenly passed away. He made groundbreaking contributions to the chapter by setting up the chapter team and chapter structure. Brad was well respected throughout the USGS and the broader scientific community and was a close friend and colleague to many. He was involved in a number of research endeavors, including mapping global land cover, characterizing phenology from Earth observation data, and assessing biological carbon sequestration for the US. Brad was a pioneer in the fight against global warming and a strong advocate for the conservation of Earth's natural resources. A leader in the land-change science and Earth observation communities, Brad made great efforts to tackle society's most urgent issues.

# Chapter 6. Land Cover and Land-Use

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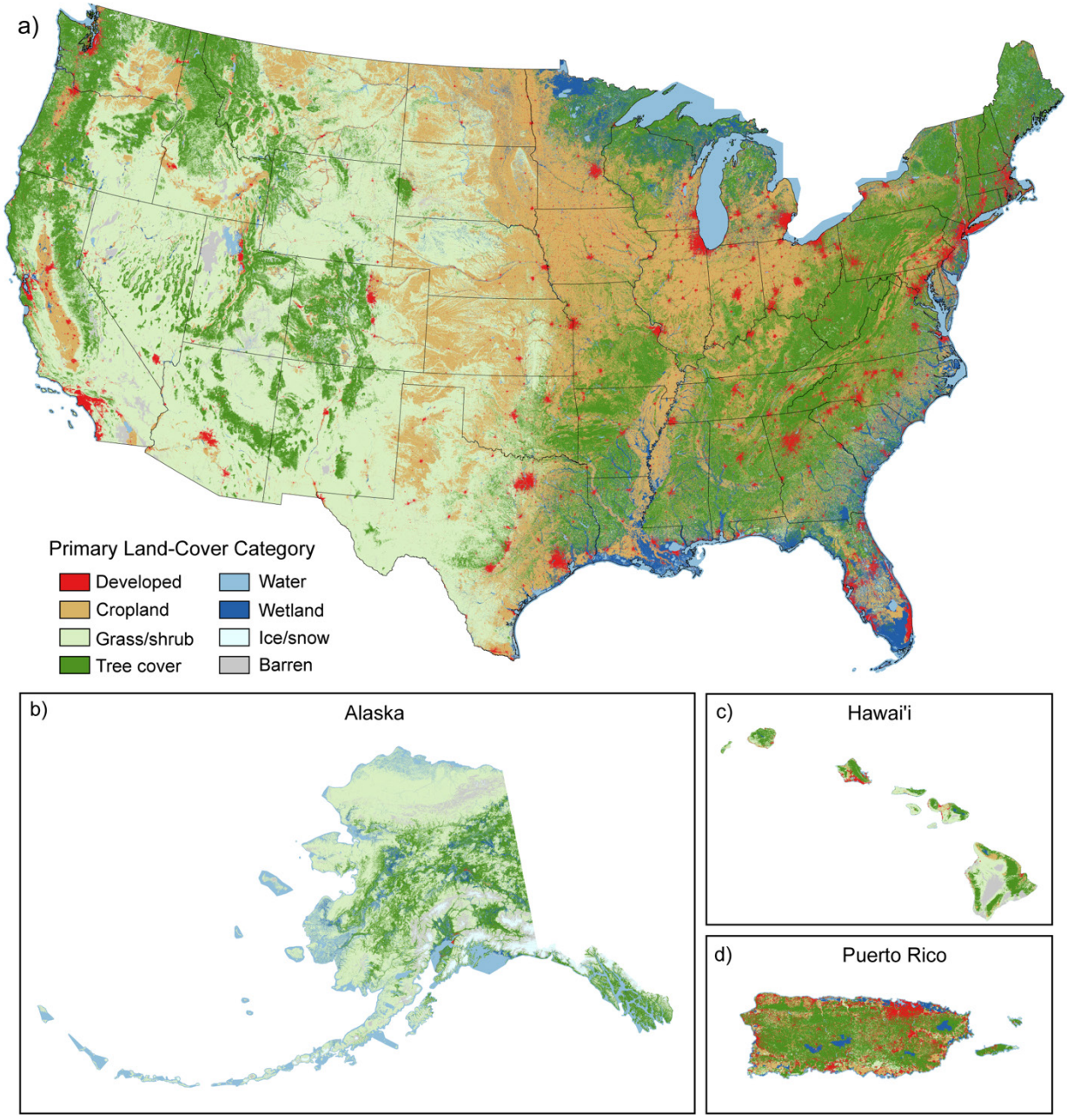
# Introduction

As Earth's climate changes, many critical aspects of the land system are at risk. "Land system" refers to both land cover (the physical organization of the land surface) and land use (the intentional ways humans interact with the land). Land system here also refers to the physical and ecological functions of land and changes in organization and function over time. Escalating concerns about how climate and global environmental change impact land systems and ecosystem sustainability have driven extensive research efforts to understand these complex interactions.[1,2,3,4,5] This chapter considers three broad categories describing the value of land systems to society and risks associated with climate change: 1) goods and services provided directly by land systems, 2) resilience of land systems in the face of disturbance, and 3) availability of options for future land use.

Analysis of these topics depends in part on reliable descriptions of historical and current land cover and land use. Satellite remote-sensing platforms and ground-based training data provide records of past and current land cover over the United States on a yearly basis (Figure 6.1).[6,7,8] Land-cover changes are caused by humans and ecosystem processes, with compounding effects from climate change, and are unevenly distributed in space and time. Some areas experience frequent land-cover changes from natural or human-caused disturbance (Figure 6.2), while other areas show progressive shifts in land cover, for example with the expansion of developed areas (Figure 6.3). While broad land-cover categories are relatively stable through time when aggregated to the national scale, varying by less than 10% from their 1985 values over the period 1985–2020, modest multidecadal changes within land-cover categories are still evident (Figure 6.4).

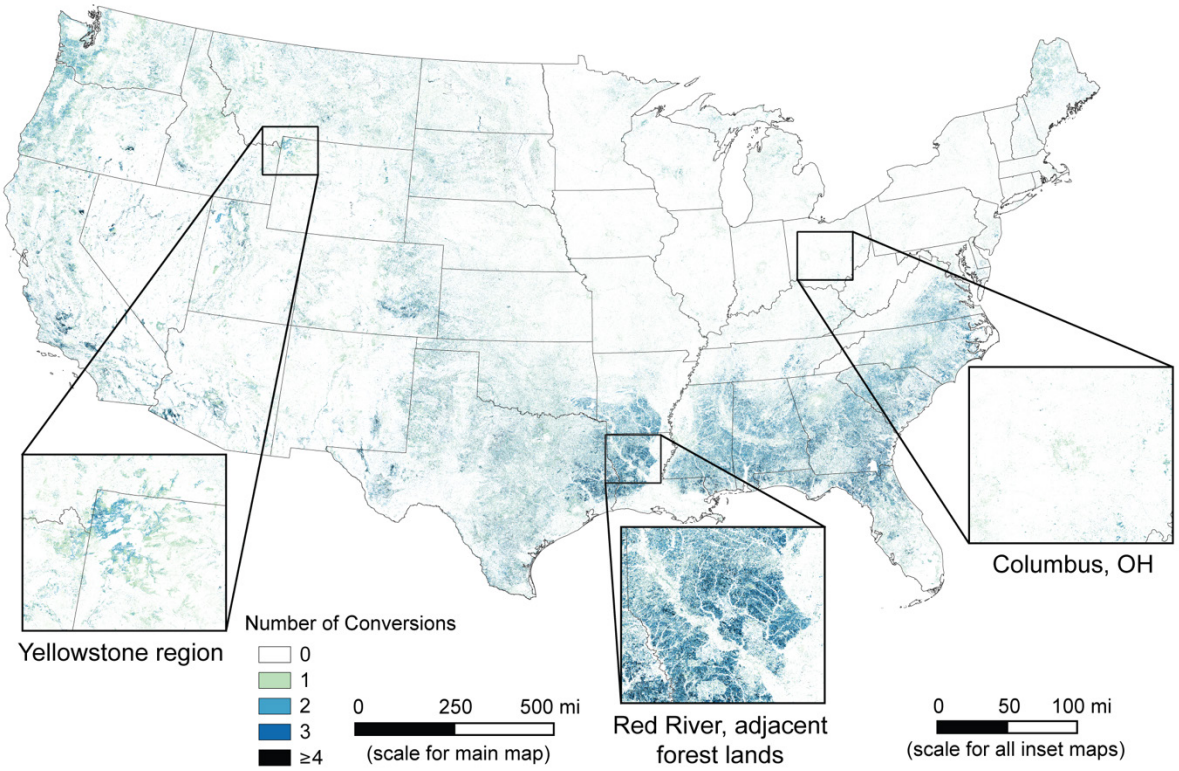
## Present-Day Land Cover




**The United States is characterized by complex spatial distributions of developed, managed, and natural land-cover types.**

**Figure 6.1.** Data shown here are from different sources and for slightly differing time periods: (**a**) contiguous US from Land Change Monitoring, Assessment, and Projection [LCMAP] data for 2020; (**b**) Alaska from the National Land Cover Database for 2016; (**c**) Hawai'i from LCMAP for 2019; and (**d**) Puerto Rico from Coastal Change Analysis Program data for 2010. Developed land cover is clustered around urban centers, croplands dominate the central contiguous US, and managed and natural forests, grasslands, and shrublands are widely distributed. Figure credit: Oak Ridge National Laboratory and USGS.

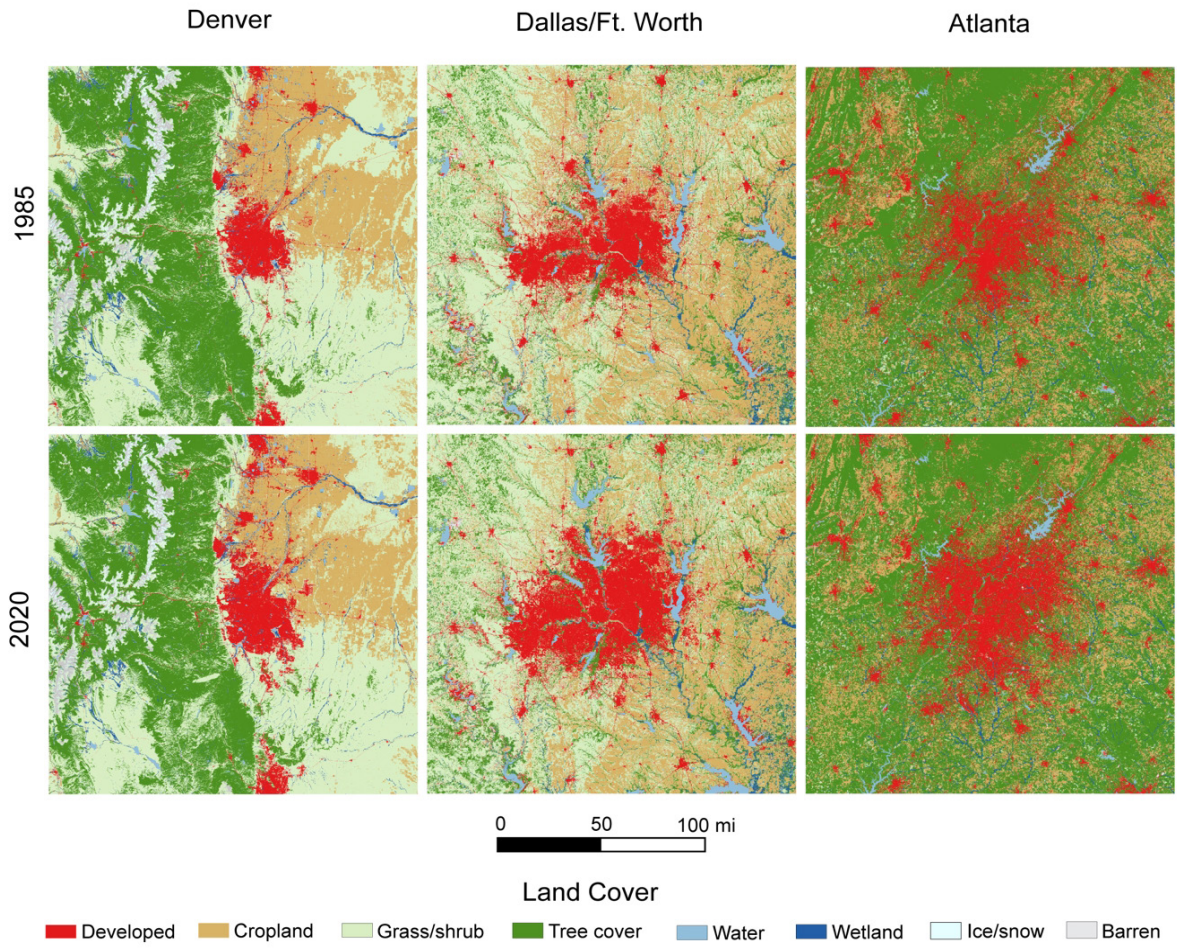
## US Land-Cover Conversions, 1985–2020




**Land-cover change can result from development, forest management, wildfire, and other causes.**

**Figure 6.2.** Superimposed on the complex mosaic of land-cover types are patterns of land-cover change that vary among regions. The number of land-cover conversions is shown over the period 1985–2020. A conversion is defined for each LCMAP (Land Change Monitoring, Assessment, and Projection) 30 m x 30 m grid cell as a change between years from one primary land-cover category to another. The primary land-cover categories are as follows: developed, cropland, grass/shrub, tree cover, water, wetland, ice/snow, and barren. The frequency of conversion depends on multiple interacting factors. Development drives expansion of urban centers (e.g., around Columbus, Ohio). Forest management causes multiple land-cover conversions between forest and non-forest categories over decadal timescales while maintaining a consistent land use (e.g., around the Red River). Wildfire can cause large and long-lasting changes in land cover (e.g., in the Yellowstone region). The warming climate influences land-cover change by impacting development patterns, harvest recovery dynamics, and wildfire frequency and intensity. Figure credit: Oak Ridge National Laboratory and USGS.

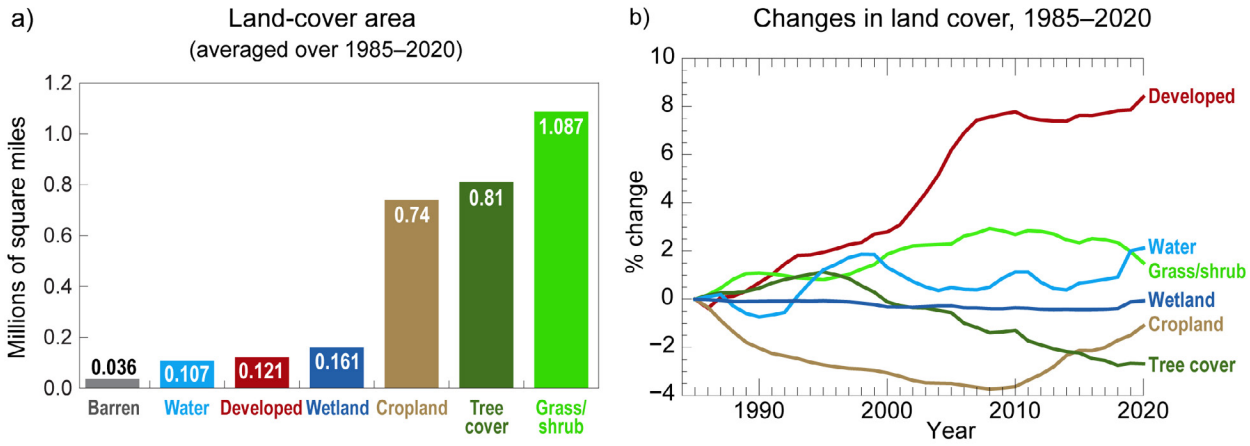
## Expansion of Developed Land Cover




**Increased development decreases natural and managed land cover.**

**Figure 6.3.** Continuing expansion of development into vegetated land changes the array of climate-related risks to land system goods and services (KM 6.1), land system resilience (KM 6.2), and future land-use options (KM 6.3). Land-cover changes from 1985 to 2020 are shown for three urban areas: Denver, Dallas/Fort Worth, and Atlanta. Figure credit: Oak Ridge National Laboratory and USGS.

### US Average Land Cover and Land-Cover Change




**Developed land is increasing, while land with tree cover is on the decline.**

**Figure 6.4.** Grassland, shrubland, cropland, and tree cover make up a large majority of the US land cover (**a**), and the area of these broad land-cover types changes relatively slowly over time when aggregated over the contiguous US. When expressed as a percentage change from the total land area for each cover type relative to values in 1985 (**b**), developed land has the largest increase through 2020. The area with tree cover has been declining since the mid-1990s, while the area of cropland declined through about 2010 and increased again through 2020. Figure credit: Oak Ridge National Laboratory and USGS.

## Key Message 6.1

### The Goods and Services Provided by Land Systems Are Threatened by Climate Change

Climate change has increased regional intensity and frequency of extreme rain, droughts, temperature highs, fires, and urban floods (*high confidence*), posing increased risks for roads and other infrastructure, agricultural production, forests, biodiversity, carbon sinks, and human health (*high confidence*). Climate-driven increases in wildfire extent and intensity are threatening the ability of some western forests to provide valued goods and services (*high confidence*). Climate change has disrupted the ways that people interact with the landscape for spiritual practices, recreation, and subsistence (*high confidence*).

### *Infrastructure, Public Safety, and the Built Environment*

People expect land to provide a solid and permanent footing for infrastructure, public safety, and the built environment. Climate change threatens this in numerous ways, including increases in erosion, permafrost thaw, slope failure, fire, flooding, and shoreline retreat. Land-use changes themselves can interact with these climate impacts in complex ways (KM 6.2).

As sea levels rise, coastal infrastructure is increasingly exposed to risks of flooding and wave action from storm surges and nuisance flooding during high tides, with low-income coastal communities facing greater risks due to fewer resources for response (KMs 9.2, 23.1). The Atlantic and Gulf Coasts are particularly vulnerable to high tide flooding.[9] Decadal-scale variability in Great Lakes water levels drives shoreline erosion (KM 24.5). Increases in the magnitude and frequency of heavy rain in a warmer climate heighten the risk of damage from river flooding, especially where infrastructure for water storage, treatment, and

transfer becomes overwhelmed. Increased storm rainfall puts roads and buildings at greater risk of damage by landslides.[10] For example, Hurricane Maria, a Category 4 storm in 2017, caused substantial damage and fatalities in Puerto Rico, as well as more than 70,000 landslides.[11]

Warming of colder regions such as Alaska presents significant risks. Damage to roads and the Trans-Alaska Pipeline System is occurring due to ground destabilization as permafrost thaws.[12,13] As steep, rocky terrain warms and thaws, rockfalls can increase,[14] and as tidewater glaciers retreat, newly destabilized slopes in front of glaciers can collapse into water, causing potentially hazardous tsunamis.[15,16]

The USGS[17] provides emergency assessment of postfire debris-flow hazards (Focus on Western Wildfires). Fire and postfire debris flows increasingly threaten infrastructure and public safety as a warming climate and increased drought raise the risk of large, intense fires.[18,19,20,21] Notable among recent examples was the debris flow following the Thomas Fire in Southern California, which killed 23 people, damaged 558 structures, closed a major highway for 13 days, and caused more than $1.15 billion in damages (in 2022 dollars; Figure 6.5).[22,23] Risks to water supply and quality continue for years after a fire, as erosion washes excess sediment and pollutants downstream,[24] shortening the lifespan of water-storage reservoirs.[24,25,26] Sediment production is projected to double in one-third of western US watersheds by 2050 due to increased fire and extreme rain.[26]

## Damage from Postfire Debris Flows

**Postfire debris flows threaten public safety.**

**Figure 6.5.** Photos show property destroyed by postfire debris flows in Montecito, California, caused by intense rain on January 9, 2018, falling on areas burned by the Thomas Fire in the previous month. Both contributing events—a large wildfire and extreme rain—are projected to become more frequent with climate change. Photo credits: Jason W. Kean, USGS.

The Southwest faces additional challenges to infrastructure and public health and safety from increased airborne dust,[27,28,29] which can carry human disease and result in traffic accidents.[30,31] Vegetation loss during drought can cause marginally stable land to transition to actively migrating sand dunes, some of which damage buildings and roads.[32,33]

## Agriculture: Crops and Rangelands

Land provides essential services by supporting the production of food for people, feed for animals, and forage for wildlife. Climate change has led to increased extremes of both temperature and precipitation, with increased risks to crop yield (KM 11.2) and associated impacts on land-cover and land-use change (LCLUC). Crop yields in the US continue to increase but are subject to large year-to-year fluctuations driven by environmental stresses[34,35] and have become increasingly sensitive to water availability over the past two decades.[36] Yield loss associated with warming has resulted primarily from drought, with heat stress playing a secondary role.[37] Flooding also causes crop damage; during 1981–2016 in the US, inundation-induced yield loss was comparable in magnitude to that caused by extreme drought.[38]

In arid and semiarid lands of the Southwest, livestock overgrazing, oil and gas extraction, and off-road vehicle use amplify the effects of warming[39] by damaging vegetation and biological soil crusts,[40] further increasing dust production. The spread of invasive plants exacerbates this transition, leaving landscapes less adaptable to warming.[41] Water extraction by humans lowers water tables, stressing plants, drying lakebeds, and increasing dust production. These factors, together with the warming-induced drought, reduce the productivity and carrying capacity of US rangelands (KM 28.3).

## Forests and Biodiversity

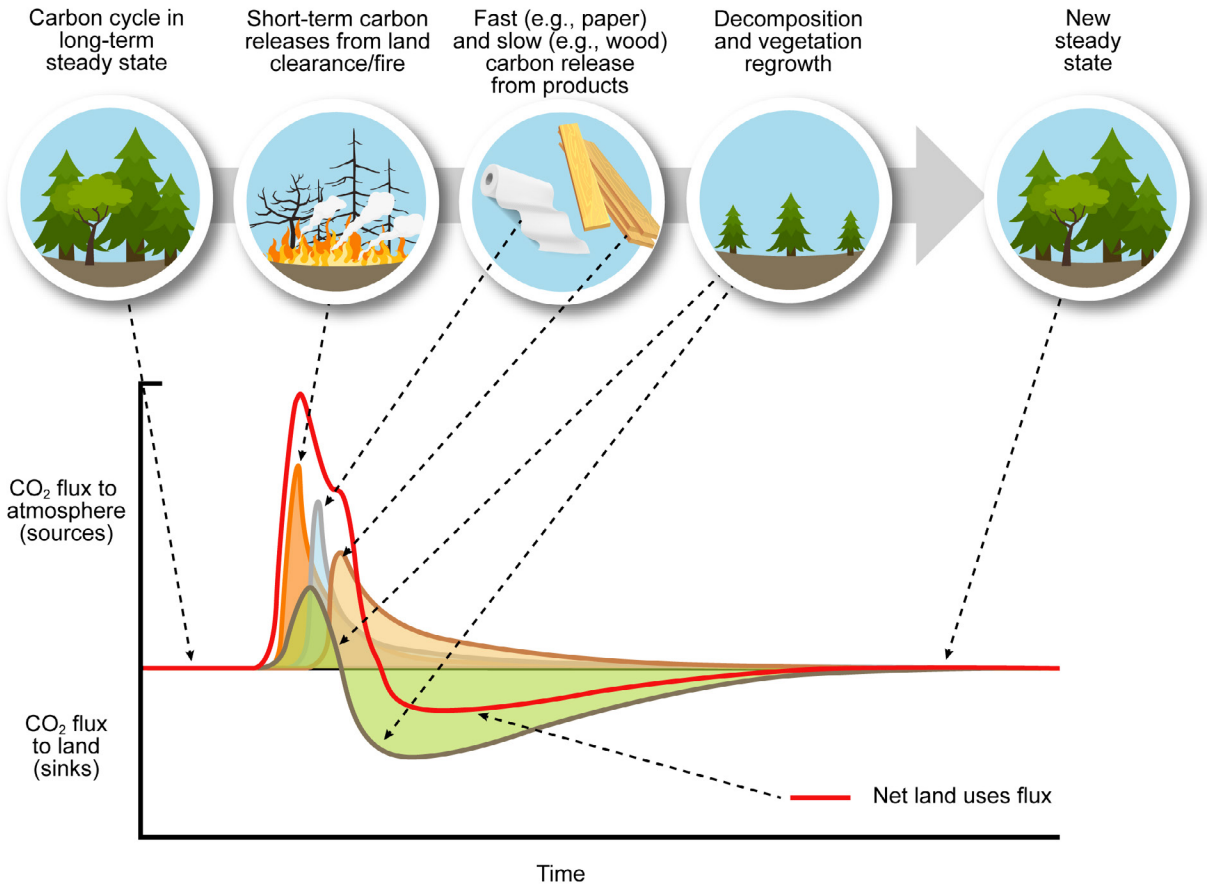
Forests provide critical value to society by supplying a wide range of wood products, protecting water quality, supporting biodiversity, and providing recreational opportunities and spiritual and cultural benefits. Forest land cover can reduce warming locally by providing increased evaporation and shade.[42] The effects of land-use change on forest goods and services, including the value of biodiversity, are still being explored.[43,44,45] In some cases, forest management can increase biodiversity and offset regional losses due to urbanization, but future losses of biodiversity due to climate change may be greater than reforestation offsets.[46]

Multiple interacting factors drive changes in goods and services from forest lands, including development, abandonment and expansion of agricultural land, and incentives for reforestation and conservation.[47] Mixed land uses such as agroforestry are expected to increase soil water infiltration compared to agriculture alone, providing protection against warming, drought, and soil erosion due to overland flow during extreme precipitation events.[48] Forest land-use transitions intended to mitigate climate change must be carefully assessed to prevent unintended consequences, such as net losses of carbon, biodiversity, habitat, soil quality, or other ecosystem services when converting mature forest to bioenergy crop cultivation (e.g., Harper et al. 2018[49]).

## Natural and Managed Carbon Sinks

Land ecosystems provide an important service to society by sequestering a fraction of the carbon emitted to the atmosphere through fossil fuel combustion and land use. The net carbon balance at any location is the result of multiple simultaneous losses and gains related to plant growth and organic matter decomposition (KM 8.1), historical and current LCLUC, and climate conditions including atmospheric carbon dioxide ($CO_2$) concentration and local rates of nitrogen deposition (Figure 6.6).[50] Northern Hemisphere forests are important carbon sinks (KM 7.1).[51] Boreal and tropical forests are both globally important carbon sinks, and since 1992 the boreal forest sink has been increasing in importance relative to the tropical forest sink.[52] Other ecosystems, such as grasslands,[53] wetlands,[54] and some agricultural systems (KM 11.1)[55] also contribute to the carbon sink, with complex and uncertain interactions with management actions.

## Carbon Flux Response to Land-Cover and Land-Use Change




**Changes in land cover and land use affect the fluxes of carbon taken up on land or released into the atmosphere, with impacts on these fluxes lasting for decades to centuries.**

**Figure 6.6.** Land-cover or land-use changes can trigger complex sequences of carbon release and uptake. The example shown here illustrates a single idealized land-use event and the multiple impacts of such an event on carbon release and uptake fluxes. Net carbon flux from land use (red line) depends on time since disturbance, with climate change impacting all the component fluxes. Component fluxes include immediate losses from land clearance and fire (orange line), fast release of carbon from decomposition of forest products such as paper (blue-gray line), slow release from forest products such as lumber (brown line), and initial decomposition of litter and soil organic matter followed by carbon uptake during regrowth (dark gray line). The processes represented here typically span multiple decades to a century or more. In this illustration the net carbon flux (red line) eventually returns to zero, indicating that the influence of a single event has a finite period of impact on fluxes. During this period of impact, accumulated carbon losses (summed area of the red line above the zero flux level) can differ from accumulated carbon gains (summed area of the red line below the zero flux level), resulting in new steady states with either more or less total carbon storage than before the land-use event. Multiple events such as this can occur over time at a single location and can overlap each other in time, leading to even more complex patterns of fluxes. Figure credit: Oak Ridge National Laboratory.

While highly variable from year to year, the fraction of emissions taken up by land ecosystems has remained relatively stable on decadal timescales (Box 7.2). Recent evidence suggests that plant response to increasing atmospheric $CO_2$ is the dominant factor driving the land carbon sink at global scales.[56,57] A significant part of the land sink is also attributed to recovery following natural disturbances and legacy effects of past LCLUC.[58,59,60,61]

### *Intrinsic Value*

Impacts of climate change are transforming landscapes in ways considered intrinsically detrimental. Communities with especially strong ties to place and local ecosystems, including but not limited to Tribal and Indigenous groups, may suffer declining cultural and spiritual connections with the land through these changes (KM 15.2),[62] such as through the drying of formerly perennial springs and streams that have spiritual significance[63] or through reduced opportunities for traditional harvesting of plants that decline as environmental conditions change. In central and northern Alaska, traditional methods of hunting on sea ice have become less feasible, and destabilization of thawing permafrost jeopardizes long-occupied communities (KM 29.3).[64,65] Subsistence and recreational fishing are reduced by ecosystem changes, some of which are climate driven and will worsen with additional warming;[66] for example, decreased salmon abundance has profound negative effects on many Tribes in the Northwest (KM 27.1).[67] Other recreational land uses are limited by the changing seasonality of river flows, loss of ice and snow, and loss of access to areas recently burned.

## Key Message 6.2

## Changes in Climate and Land Use Affect Land-System Resilience

Changes in climate and land use affect the resilience of land ecosystems and thus the fate of the services they provide (*high confidence*); for example, increasing drought reduces the ability of forests to store carbon. Climate and land-use change interact, and these interactions present challenges as well as opportunities for maintaining ecosystem resilience (*high confidence*).

### *The Value of Resilience*

Ecosystem resilience—defined here as the capacity of a land system to respond to disturbance by resisting damage and/or recovering quickly, maintaining its essential structure and function—determines the persistence of services amid LCLUC. Disturbance is defined here as any discrete event (e.g., fire, flooding, drought, wind, geological hazard, pathogen, insect infestation, etc.) that occurs outside the range of natural variability (e.g., vegetation phenology, climate interannual variability, etc.) of the land system.[68] Management also impacts land systems, with the potential to both increase or decrease resilience. Resilience enables natural and built systems to maintain the continued delivery of goods and services in the face of changes. Climate change is affecting ecosystem resilience, triggering responses such as shifted distribution of species and reduced biodiversity (KM 8.2),[69,70] changed timing of biological processes,[71,72] altered success of existing land uses,[73,74] and lowered ability of systems to resist and recover from land-use activities and natural disturbance.[75] Ecosystems in the US have experienced increases in average temperature and extreme heat,[76] increased drought,[77] and increased intensity and frequency of extreme precipitation.[78,79] Changes in precipitation characteristics and warming have driven an increase in aridity in much of the United States,[80,81] with lasting impacts on ecosystems.[82] Land use and management affect ecosystem resilience and interact with climate change to determine the structure and function of the land system (KM 20.3).[83,84] The fact that human decisions can influence resilience provides opportunities for climate mitigation (Ch. 31) and adaptation (KM 6.3; Ch. 32) and is a foundation for nature-based solutions to climate change,[85] as well as an opportunity to improve resilience through management actions informed by Indigenous Knowledge (KM 16.2).[86]

## *Interactions Between Climate Change and the Land System and Effects on Resilience*

Climate change and land use individually and interactively affect land systems, the services they provide to humans, and the resilience of ecosystems. Climate change alters landscape characteristics and management outcomes, which drive changes in land use and/or land cover (Figure 6.7). Land use itself impacts the land system, with potential to both increase and decrease resilience. Land use and land cover help determine climate via effects on carbon, water, and energy exchange with the atmosphere.

Climate change affects ecosystem resilience, structure, and function. For example, tree mortality events have resulted from drought and/or high temperatures in the temperate and boreal forests of western North America,[87,88] and widespread death of many tree species has been linked to climate change through wildfire and insect attack.[89,90] Warming-induced drought is causing widespread mortality of forests in the Southwest US.[91] Increased tree mortality and impaired regeneration decrease the resilience of forests (KM 7.1).[92,93]

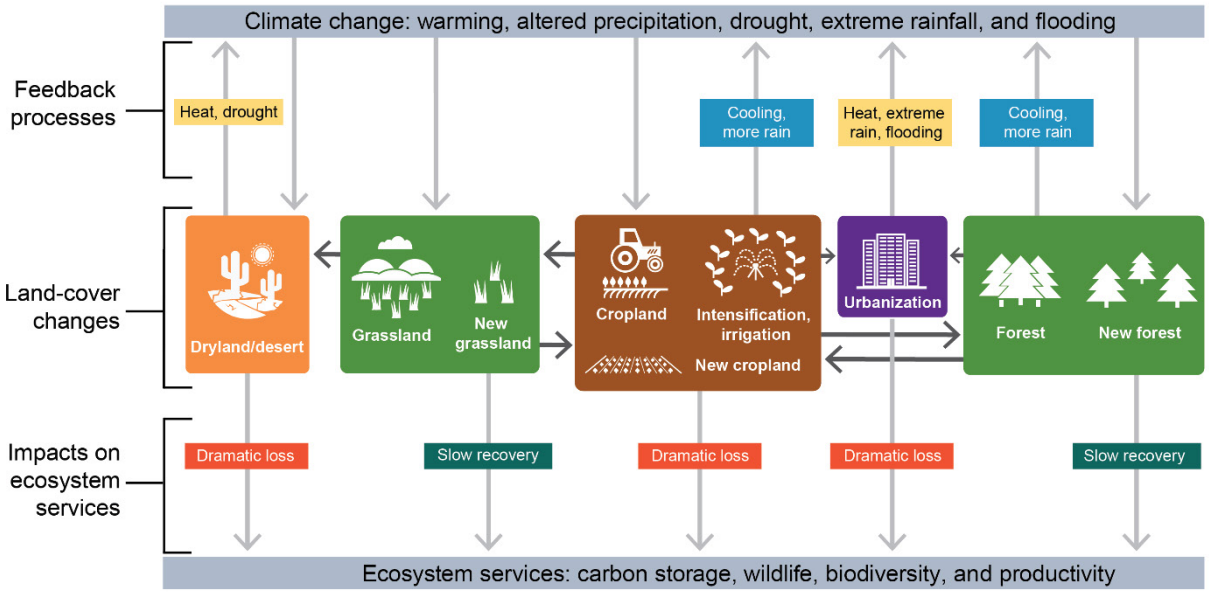
Increases in average temperature and altered precipitation patterns cause changes in species composition,[92,93] such as encroachment of shrubs into grasslands[94] and invasion by exotic grasses into rangelands, drylands, and forests.[41,95] Exotic grass invasion increases fuel loads and the ability of fire to move across the landscape, often resulting in large increases in fire risk.[41,96,97] By reducing fuel moisture, hotter and drier climates lengthen the wildfire season and lead to larger, more severe fires.[20,21] Increased wildfire frequency and severity can result in the loss of soil organic carbon through combustion[98] and postfire erosion.[24] In boreal systems, increased fire frequency may lead to changes in forest type,[99] while streamflow changes and permafrost thaw may trigger transition from peatland to forest.[100,101] Interactions between fire, climate change, and human development are multifaceted and include not only warming-induced increases in wildfire but also management actions to reduce wildfire fuel, the effects of fire on human populations, postfire recovery, and fire-induced changes in forest type (KM 8.1). Drought, wildfire, and unsustainable land-use practices cause land to lose productivity, which may trigger desertification in arid and semiarid regions.

Changes in land cover influence local and regional climate through both biogeochemical and biophysical pathways. The biogeochemical effects of vegetation loss, including both immediate $CO_2$ emissions and missed capacity for carbon sequestration (KM 6.1), have a warming impact at the planetary scale.[102] Vegetation loss causes immediate changes to local and regional climate through biophysical effects (e.g., Jiang et al. 2021;[103] Wang et al. 2016[104]), including exposed ground or snow (cooling the surface by reflecting more sunlight), reduced evapotranspiration (warming the surface and reducing moisture supply for rainfall), and a smoother surface (warming the surface by reducing heat loss to the atmosphere). The net impact of land-cover change on local climate depends on season, background climate, and vegetation type. Across the United States, forest disturbance or forest loss during the 2000s and 2010s caused a net local warming at both evergreen and deciduous sites in arid/semiarid, tropical, temperate, and boreal zones.[105,106] This occurred because warming from the loss of transpiration more than compensated for the cooling effects of the more reflective land surface following forest loss; exceptions were found during boreal winter at high latitudes where strong cooling resulted from high albedo of exposed snow.[105,107] Similarly, climate over forests is cooler than the surrounding croplands and urban areas, and the increase of forest cover following agricultural abandonment during 1920–1990 is connected to the observed cooling trend in the Southeast US.[108]

Indirect interactions also have impacts on US ecosystem resilience.[1,109] Land-use decisions that consider the interactions of climate change and management can maintain and promote ecosystem resilience.[83,110] For example, the thinning of some western forests that are experiencing drought increases the resilience of the forests to future trends of warming and drying.[111]

Changes in climate and land use offer opportunities for mitigation and adaptation, such as post-disturbance restoration of lands using climate-adapted species, which could increase biodiversity and resilience to climate change.[112] Increasing land-based carbon storage may be achieved by shifts in land management (KM 6.3), for example by afforestation (Ch. 7), altered grazing practices (Ch. 11),[53] modified crop management (Ch. 11), conserved agricultural lands,[113] active restoration of disturbed lands,[114] and the use of prescribed fire to avoid wildfire.[115]

### Land, Climate Change, and Ecosystem Resilience




**This figure shows the primary land-use and land-cover changes, their interactions with climate, and impact on ecosystems.**

**Figure 6.7.** Land-use and land-cover changes interact with climate change, leading to lasting impacts on ecosystem services and resilience. Black arrows represent land conversions, and gray arrows represent impact or feedback processes supported by existing literature. Figure credit: University of Connecticut, USDA Forest Service, USGS, and Oak Ridge National Laboratory.

## *Land System Resilience Risks Associated with Increasing Development*

Among all classes of land-cover change in the contiguous United States between 1985 and 2016, the largest net change in any class was an estimated gain of 50,660 square miles (131,209 km$^2$) of developed lands, at an average rate of 1,634 square miles (4,233 km$^2$) per year, primarily at the expense of forest and agricultural land,[116] a trend that continues to the present (Figure 6.4). Urban heat island effects exacerbate the impacts of warming on heat hazards, which disproportionately harm low-income communities (KM 12.2; Figure 12.6; App. 4). Warming-induced increases in precipitation extremes lead to higher flash flood risks, with especially devastating effects in urban regions where impervious surfaces cannot absorb rainwater. Although widespread increases in intense rain are evident,[117] river flooding trends are not consistently apparent across the US at present (KM 4.2);[118] however, in urbanized basins, as urban development expands, the size of flood peaks increases.[117,119,120] A resilient urban infrastructure, therefore, must be able to accommodate increased runoff from extreme storms (KM 12.2). Urbanization, through both urban land cover and increases in human-caused fine particulate matter, can alter atmospheric convection and precipitation, leading to stronger storms and more intense precipitation.[121,122,123,124] Urban heat islands reduce low clouds,

which can increase plant water stress and possibly play a role in increasing wildfire risk, particularly in the wildland–urban interface.[125,126]

The adverse effects of urbanization on climate and ecosystems can be partly alleviated through sustainable practices designed to improve urban resilience. Urban greenspace (e.g., urban forest, farming, gardening) can mitigate the urban heat island effects and flooding risks[127,128,129] with varying degrees of effectiveness. While urban vegetation sequesters carbon during the growing season, the annual net carbon flux is uncertain.[130,131,132] Additionally, urban farming brings food security benefits, with yields comparable to conventional agricultural yields.[133]

Increasing energy demand, combined with new extraction technologies, has resulted in an average of 50,000 new oil and gas wells established per year throughout central North America since 2000.[134] Infrastructure for horizontal drilling and high-volume hydraulic fracturing has transformed millions of acres into industrialized landscapes, with reductions in ecosystem resilience, biodiversity, and the land carbon sink (e.g., Allred et al. 2015[134]). Reclamation of wells could become less successful with climate change.[135] The efficacy and resilience of renewable energy systems are expected to be affected by climate change in ways that will vary with generation type and location [136] and may strain the energy system (KMs 5.1, 5.2, 5.3).

## *Land System Resilience Risks Associated with Changes in Agriculture*

After declining for multiple decades, cropland area in the United States increased at a rate of approximately 1,500 square miles (approximately 4,000 km$^2$) per year during 2008–2016 (Figure 6.4b),[137] attributable to increased domestic demand for corn ethanol and global demand for agricultural commodities as well as changes to conservation and crop insurance programs, interest rates, and possibly climate change–driven crop migration.[138,139] New croplands tend to occupy areas with marginal biophysical characteristics (e.g., erosive soils, nutrient deficiency, climatic stress) but displace grasslands and conservation easements that are higher-quality wildlife habitat than the remaining natural lands.[137] Expansion of agricultural area in the north-central United States has led to fragmentation of the remaining grassland, which limits the dispersal and population of native species (e.g., Wimberly et al. 2018[140]) and is expected to reduce ecosystem resilience. Conversion of grassland to cropland also contributes to carbon emissions from loss of soil organic carbon (KM 11.1).[141] The recovery of plant biodiversity, productivity, and soil carbon following agricultural abandonment is slow,[142] but the potential recovery of carbon in lands released from agricultural use is substantial, as has been shown by the large soil carbon gains made in land under the Conservation Reserve Program (KM 11.1).[113] Soil carbon increases, as well as increases in other ecosystem services, can be accelerated through activities such as deliberate revegetation with woody and herbaceous perennials.[143]

Agricultural extensification influences precipitation, with the direction of change depending on the region and the type of natural land cover prior to its conversion to cropland. For example, replacing grassland with cropland over the Great Plains can cause summer precipitation to increase.[144] Studies suggest that, in addition to increased area, intensification and irrigation are major causes of the observed increases in precipitation and decreases in temperature in the central US and Midwest[145,146,147,148]—changes that provide potentially more favorable conditions for crops and surrounding ecosystems. Land conversion to cropland without intensification was not associated with the observed cooling.[146]

## Key Message 6.3

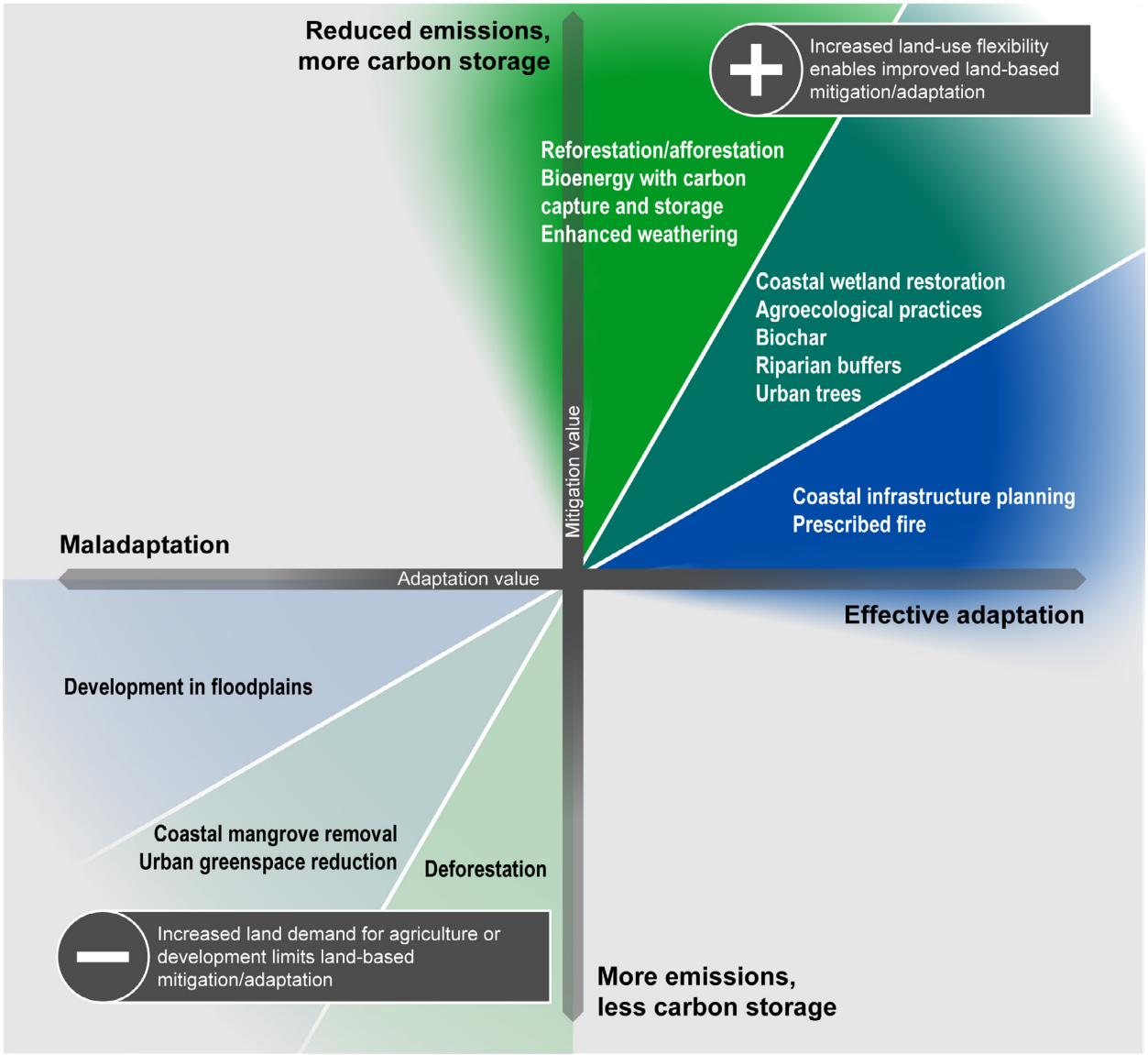
### Mitigation and Adaptation Priorities Will Increasingly Constrain Future Land-Use Options

The future of land use in the United States will depend on how energy and agricultural technology evolves, how the climate changes, and the degree to which we prioritize climate mitigation and adaptation in land-use decisions (*high confidence*). US cropland area had been declining but has rebounded somewhat over the last 1–2 decades (*high confidence*). Future cropland needs will depend on uncertain factors such as agricultural technology improvements, dietary shifts, and climate change impacts (*medium confidence*). Decarbonization will require a continued expansion of solar and wind energy generation and transmission infrastructure (*very likely*, *high confidence*) and may involve large land-use changes toward land-based mitigation measures, including reforestation, other natural climate solutions, and bioenergy crops (*low confidence*).

## *Future Land-Use Scenarios*

People value the ability to choose among multiple land-use options, although the ability to make these choices is not always experienced equitably across society (KM 20.3). There are increasing and competing demands for future land-use changes to support agriculture, housing, and infrastructure; to contribute to climate change mitigation and adaptation; and to conserve and possibly restore natural lands for biodiversity, resilience, and spiritual or recreational use. Scenario analysis is used to explore different climate mitigation "storylines," known as Shared Socioeconomic Pathways (SSPs; Table 3 in Guide to the Report), for how global land use, energy systems, and greenhouse gas emissions might evolve together under a set of standardized background driving forces such as changes in population, technology, and governance.[149,150] Land-use representation within the range of SSPs includes differences in land-use regulation, land productivity, trade, land-based mitigation and adaptation (Figure 6.8), and food/diet choices, along with a corresponding range of land-use trends that result from these drivers (Figure 6.9).

## Mitigation and Adaptation Value of Future Land-Use Choices



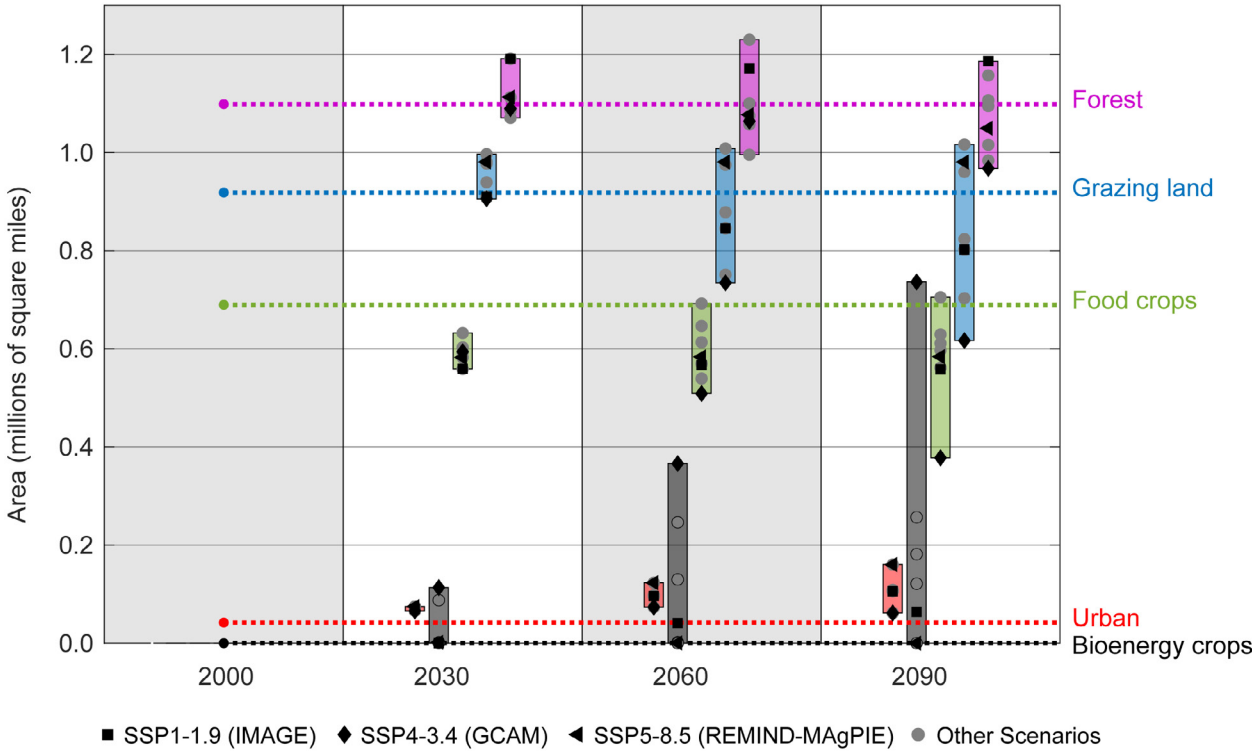

**Future land-use choices have implications for climate mitigation and adaptation.**

**Figure 6.8.** Future land-use choices can contribute to mitigating global climate change by reducing emissions or storing carbon (green), help individuals or communities adapt to the effects of global change (blue), or simultaneously support both mitigation and adaptation (green-blue), as shown in the upper-right quadrant. Flexibility in land use for mitigation and adaptation depends on background factors, including agricultural technology improvement, income growth, food waste reduction, and international cooperation. Alternately, indiscriminate land use change can lead to additional carbon emissions or maladaptation (lower-left quadrant). Many of these land-use choices are discussed elsewhere, including Key Messages 7.3 (forest adaptation), 9.3 (coastal adaptation), 11.1 (agricultural adaptation), and 12.3 (urban trees), as well as Box 32.2 (carbon dioxide removal). Figure credit: NASA, University of Maryland, and Oak Ridge National Laboratory.

Future land uses in the United States have been explored under several SSPs and at multiple spatial scales.[151] Future land use within the SSPs (Figure 6.9) is projected to involve substantial departures from historic trends (Figure 6.4), with determinants of change and resulting land-use patterns varying spatially and with time, based on multiple drivers including land management, demographic change, and ecological shifts (e.g., Richter and Bixler 2022 [152]). Many scenarios assume continued agricultural productivity

increases, allowing the total area of cropland for food production to remain stable or decline despite the increasing global population.[150] Future land-use changes that limit global warming include reductions in grazing land associated with lower-animal-calorie diets and climate mitigation via reforestation or forest expansion. In addition, to offset fossil fuel use in other sectors, an often-dramatic expansion of bioenergy crops (producing nonedible plant material) is included in many scenarios. Large increases in urban area and reductions in forest area often accompany scenarios that involve greater levels of climate change.[153] Although these scenarios are useful for exploring different possible land-use futures at the aggregate scale, they do not quantify the likelihood of different land-use changes.

## Scenario-Based Future Land-Use Trends




**Future land-use scenarios describe a wide range of possible land-use changes in the United States.**

**Figure 6.9.** Future land use in the 50 US states across eight different Shared Socioeconomic Pathways (SSPs) depicts increases in urban area, stability or decline in food crop area, and mixed outcomes for remaining land-use types, with large divergence among scenarios. (Data for the US-Affiliated Pacific Islands and US Caribbean are not included due to the spatial resolution of the underlying data source.) Colored bars show the range of land-use areas across all scenarios, and dashed lines indicate year 2000 values for comparison. Black symbols illustrate results for select scenarios of low emissions and high reforestation (SSP1-1.9 from the IMAGE model), moderate emissions with large nonedible bioenergy crop growth (SSP4-3.4 from the GCAM model), and high emissions (SSP5-8.5 from the REMIND-MAgPIE model), while gray symbols represent remaining scenarios. The large expansion of bioenergy crops is often taken from natural grasslands, which are not represented in this figure. Figure credit: University of Maryland, Oak Ridge National Laboratory, and NASA.

## Future Agricultural Land Use

Flexibility in future land-use decision-making may be limited by agricultural land needs. Climate change is estimated to be slowing the rate of crop yield increases globally;[154,155] future land use will depend on the ability of the agricultural sector to adapt. Modeling results indicate that climate change–driven regional crop disruptions may emerge within 2–3 decades,[156] although such disruptions would be minimized with the adoption of adaptation and intensification measures such as supplemental irrigation and updated crop varieties.[157,158] There is also evidence of agricultural system adaptation through migration of crop cultivation ranges into more favorable climates in the United States and globally.[159]

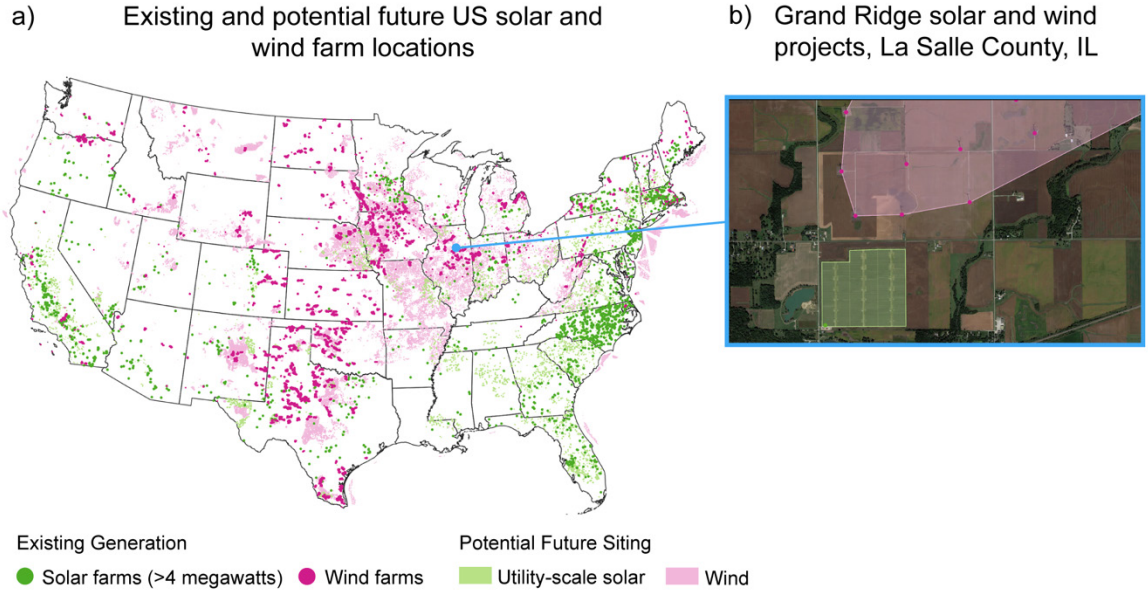
Individual farmers and landowners experience these changes in the context of increased variability in yields and income. As much as one-fifth of recent US crop insurance losses can be attributed to climate change.[160] Over time, adverse climate trends might affect the financial viability of current cropping practices and create pressure for individual producers to adopt adaptation practices (e.g., earlier planting dates, new crop varieties, modified tillage practices)[161] or switch crops. Such impacts will disproportionately affect small rural landholders (KM 11.3). Some regions are expected to see opportunities for new cropping systems[159,162] or for increasing the frequency of cropping on a given field.[163]

Future agricultural land requirements and associated climate feedbacks are sensitive to dietary choices and food waste.[164] American diets are high in meat consumption, a land-intensive food source, and universal adoption of USDA dietary guidelines would lead to a net reduction in the total biophysical land requirement for US agriculture.[165] Shifting toward diets even lower in animal products—potentially via novel plant-based meat substitutes[166]—could spare additional land and enable restoration of natural ecosystems.[167,168] US agricultural land futures could also be influenced by a continuation of the reduced household food waste observed during the COVID-19 period.[169,170]

## Future Land Use for Mitigation

Mitigation scenarios that limit global warming to 1.5° or 2°C (2.7° or 3.6°F) above preindustrial levels imply large expansions of renewable energy production, electricity transmission, and land-based carbon mitigation (Ch. 32).[171] In scenarios of net-zero emissions by 2050, wind turbines may be visible across more than 130 million acres, an area greater than Colorado and Wyoming combined (Figure 6.10).[172] However, individual wind turbines have a small physical footprint, and can be sited in areas of intensive agriculture (Figure 6.11).[173] While solar farms are more land-intensive than wind- and fossil-derived electricity sources,[174] it may be possible to integrate them into agricultural landscapes in ways that preserve or even enhance agricultural production.[175] Decarbonizing energy systems will require a multifold expansion in global production of key metals and minerals,[176] although proposals to build new mines or expand existing mines in the United States have often faced intense local opposition.[177]

## Possible Future Wind and Solar Power Siting




**Reaching net-zero emissions will require many new wind and solar projects across the US.**

**Figure 6.10.** Decarbonization will require an expanded physical and visual footprint of renewable power generation. Panel (**a**) shows current and possible future siting of wind and solar generation under a scenario that reaches net-zero emissions by 2050.[172] Panel (**b**) is a zoomed in view of the existing Grand Ridge wind and solar projects in La Salle County, Illinois and possible future siting zones. Green and pink dots show locations of existing solar and wind generation, respectively. Light green and light pink shading shows potential future siting of utility-scale solar and wind. Figure credit: Oak Ridge National Laboratory, with panel (b) background imagery © 2023 Landsat/Copernicus, Maxar Technologies, USDA/FPAC/GEO, map data © 2023 Google.

## Wind Power in Agricultural Landscapes

**Renewable energy generation can be sited in ways that minimize agricultural disruption.**

**Figure 6.11.** While wind turbines may be visible over an area of more than 130 million acres under some net-zero scenarios,[172] the actual amount of land they physically occupy is much smaller. Photo credit: franckreporter/E+ via Getty Images.

The purposeful use of vegetation to capture or store additional carbon is one of the largest but most uncertain elements in future land-use projections. Many scenarios rely on land-based mitigation measures,[178] including land-intensive reforestation or carbon-negative bioenergy production to achieve carbon dioxide removal (CDR) from the atmosphere,[172,179,180] often implying unprecedented rates of land-use change.[181] Bioenergy is the most land-intensive form of renewable energy,[174] although it is valued in integrated assessment models for providing fuels for long-haul aviation and freight transport in addition to CDR (KM 32.3). Future bioenergy expansion may rely on dedicated cellulosic biomass crops cultivated on low-value land to minimize conflicts with existing agricultural production,[182,183] with positive or negative effects on ecosystem carbon storage depending on previous land use.[184]

Existing experience with land-based mitigation measures is limited, and the efficacy of forest carbon offsets, agricultural soil carbon enhancement, and first-generation biofuel programs remains controversial.[185,186,187,188] Most of the limited CDR achieved to date has come from forest restoration and management, and current CDR deployment plans fall far short of the scale envisioned in many decarbonization scenarios.[189] In the

absence of such land-based mitigation measures, limiting global warming to below 1.5°C (2.7°F) will require even more aggressive emissions reductions[190] or breakthroughs in competing technologies such as direct air capture of $CO_2$.[191]

These mitigation trends imply new opportunities for landowners to generate additional revenues from leasing land for renewable energy generation or transmission, from government-run conservation payment programs, or from private carbon markets. However, these new opportunities also carry risks of conflict around conservation and the best use of public lands.

## *Broader Impacts of Land-Use Choices*

Future land-use choices also include adaptations to climate change such as locating infrastructure away from potential hazards, strengthening natural ecosystems as buffers to climate extremes (e.g., coastal forests and wetlands), and planting trees in urban areas to reduce heat stress.[192] Many of these activities have mitigation co-benefits (e.g., urban trees also store carbon).[193] Efforts to reduce land use–driven habitat fragmentation are also expected to decrease the risks of disease transmission from animals or insects to humans, as well as pandemics.[194,195,196] All components of the food supply system are expected to be impacted by future land-use choices and climate change,[194] which will be felt unequally across society (KM 11.2). Land-use planning in the United States will be determined by many decision-makers, including land managers at federal, state, and local levels, as well as private and Tribal landowners, and achieving consensus over future land-use decisions is expected to be challenging.[197]

# Traceable Accounts

## *Process Description*

The chapter lead (CL) and coordinating lead author (CLA) developed a list of relevant topics and the expertise needed to represent those topics in the assessment process. The CL and CLA reviewed a list of nominated authors, which included information about affiliation and expertise. The CL and CLA identified potential chapter authors from that list based on their knowledge of the field, their expertise in the topical areas, and their contribution to the diversity of the author team in terms of affiliations, gender, and race. Invitations were sent and updated as necessary to adequately cover the needed expertise.

All meetings of the author team were virtual, except for the all-author meeting held in Washington, DC, in April 2023. Consensus was built during weekly meetings of the full author team, with candidate content developed by author sub-teams through additional weekly meetings. All authors participated in developing and conducting a public stakeholder engagement workshop, and all authors participated in reviewing and responding to public comments.

For development of candidate text for each Key Message, the authors discussed the key topics that should be addressed based on their assessment of the literature, expert knowledge, and input from agency and stakeholder meetings. The authors then assigned topics according to expertise and performed a literature review to evaluate and synthesize information regarding land use and land-cover change, climate change, and related ecosystem controls. Based on this review, they developed Key Messages, central points, and examples to communicate the issues, challenges, and opportunities related to land system goods and services, land system resilience, and future land-use options.

## Key Message 6.1

### The Goods and Services Provided by Land Systems Are Threatened by Climate Change

#### Description of Evidence Base

Land-cover and land-use datasets for the US are detailed and reliable when considering a relatively small number of land-cover types and land-cover or land-use transitions, although the best available data for different regions (contiguous US, Alaska, Hawai'i, and Puerto Rico) cover slightly different time periods and use different though related methods.

There is consensus that more extreme rain will cause more landslides in a warmer climate, but the spatial distribution of anticipated future effects has not been resolved with much certainty; Gariano and Guzzetti (2016)[10] provided a synthesis of many studies that, in total, support these interpretations. Some individual mass-movement events have been attributed directly to climate change, but many landslides are caused more directly by factors without a clear link to a warming climate, such as slope oversteepening (by human construction) or local soil, bedrock, and hydrologic conditions. A broad literature base supports these inferences. The link between climate and slope-failure hazards, including the characteristics of rainfall, terrain, and burn severity that contribute to postfire debris flows (e.g., Kean et al. 2019[22]), is a rapidly growing research area.

The literature examining agricultural land practice and connections to climate change is broad and deep, covering many cropping and forestry practices in many regions across the US. There is a tendency for studies to focus more on small regions than on broad spatial patterns.

There is a long history of research into the connections between forest land cover and biodiversity, and this assessment drew on an extensive body of literature. These systems are complex, and the literature examines these connections from many perspectives.

While the topic of natural and managed carbon sinks on land is addressed by a large body of research, predictive understanding of interactions of the land carbon sink with land-use and land-cover change under a changing climate is still evolving (e.g., Zhu et al. 2018[61]).

## Major Uncertainties and Research Gaps

Land-use and land-cover datasets with good temporal coverage and detailed spatial information are still lacking or highly uncertain for high-latitude regions such as Alaska. Additional observations and synthesis of ground-based and remotely sensed data would be required to fill these gaps.

Geographic variation in the two-way interactions between climate change and agricultural practice points to gaps in understanding of the detailed mechanisms connecting agricultural practices to long-term climate variation.

Relationships between agricultural practice, forestry practice, and climate change in mixed-management agroforestry systems have received less attention than traditional cropping or forestry practices. To the extent that strong mitigation measures place higher demand on mixed-use systems for both production and carbon sequestration, additional effort would be required to fill these research gaps.

Comprehensive assessment of the many component fluxes and processes contributing to net greenhouse gas fluxes due to land-use and land-cover change is still an important gap at scales larger than a few tens of square miles. Regional and continental-scale studies continue to rely on sparse observations and relatively simple assumptions about how different disturbance types, frequencies, and intensities interact with ecological communities of vegetation and soil biota to drive long-term net fluxes between land and atmosphere.

## Description of Confidence and Likelihood

Based on strong and abundant empirical evidence, there is *high confidence* that climate change is increasing the regional intensity and frequency of extreme events, including rain, droughts, temperature highs, and fire. There is likewise a strong theoretical foundation for the attribution of these effects to human-caused climate change at present and further evidence that these effects will increase in the future as greenhouse gas concentrations rise. The empirical and theoretical basis for attributing changes in flood frequency and intensity is also robust, but not as strong as for extreme precipitation, droughts, and fire.[21,77] Based on abundant documentation, there is *high confidence* that these changes in weather and climate extremes cause risks to infrastructure, agriculture, ecosystems, and human health.

Broad empirical and theoretical understanding provides *high confidence* that wildfire is a major risk to the permanence of land carbon sinks, especially in woody ecosystems that have the potential to transition to savanna or grassland under increased fire frequency and/or severity. Other aspects of the net storage of carbon on land due to disturbances such as rotational forest harvest, windthrow, insect damage, and shifting agriculture are commonly identified as significant sources of uncertainty in estimating global or regional-scale carbon budgets.

Based on abundant documentation of climate change impacts on human–ecosystem interactions, there is *high confidence* that these impacts have negative consequences for subsistence, recreation, and spiritual practice. Some geographies and communities are more impacted than others, and fine-grained or predictive understanding of which communities and practices are most at risk is still being developed.

## Key Message 6.2

## Changes in Climate and Land Use Affect Land-System Resilience

### Description of Evidence Base

The adverse impact of climate change (e.g., increased mean temperature, extreme heat, drought) on the resilience of land systems is supported by theory and observational studies involving a wide array of ecosystems, with overwhelming evidence in the United States coming from ecosystems that are increasingly influenced by drought, wildfire, and pests (e.g., Williams et al. 2019[21]). There is also strong evidence for how the loss of natural lands leads to degradation of ecosystem services that are slow to recover (e.g., Isbell et al. 2019[142]). However, the extent to which different ecosystems may recover or management choices are able to maintain or rebuild ecosystem resilience is not well known.

Globally, there is a large body of literature on how land-use and land-cover changes might influence local and regional climate, and findings are often region- and scale-dependent. This assessment focuses on studies over subregions of the United States, some based on observational data analysis and others based on numerical model experiments. Of the observation-based studies, some took a space-for-time approach by comparing climate trends over different land types (e.g., irrigated versus rainfed cropland, forest versus cropland; e.g., Mueller et al. 2016[146]), while others were based on observations before and after sudden land-cover changes (e.g., Li et al. 2022[106]). In numerical modeling studies, land-use or land-cover changes were imposed over a corresponding subregion (e.g., intensification or irrigation over cropland in the central US or Midwest, converting cropland to forest in the Southeast) with experiments designed to distinguish the impact of land-use change from the impact of greenhouse gas warming. These studies compared model results with observed climate trends to enable the attribution of observed climate phenomena to land-use practice or land-cover changes (e.g., Alter et al. 2018[145]). Findings from these studies are mostly consistent.

Warming-induced intensification of rainfall increases the nitrate leaching from cropping systems to surface water and groundwater, which exacerbates the environmental effects of increased fertilizer application. Different land-use practices (e.g., no-tillage management versus conventional tillage) may influence nitrate leaching, but the impact remains uncertain based on recent literature, which limits the extent of this chapter's assessment on this aspect.

A rich literature base supports the idea that while interactions between climate change, land use, land-cover change, and disturbance increase the risks of adverse impacts, they also provide multiple opportunities to reduce or lessen those impacts and ensure resilience.

### Major Uncertainties and Research Gaps

The impact of urbanization on precipitation and other storms has been a topic of increasing research interest. Studies based on numerical modeling found a clear signal related to the enhancement of storm severity and precipitation (e.g., Debbage and Shepherd 2018[119]). However, observational data show a large degree of uncertainty and regional dependence. This is an important research gap.

Although geographically widespread increases in intense rain are evident, flooding trends are not consistently apparent at present.[118] Whether intense rain leads to flooding depends on soil type and land use, urban water-conveyance capacity, and how well the urban storm drainage system is maintained.

There are important uncertainties related to interactions between invasive species, disease, and natural disturbance. There is some evidence that changes in temperature and precipitation, as well as altered fire regimes, may negatively impact the competitive ability of native species, facilitating invasion by pests and pathogens (e.g., Ravi et al. 2022[41]). However, the outcomes are variable and seem to depend on multiple factors.

Research gaps and uncertainties also exist for the interactions of climate change with land-based renewable energy. Current research provides inconclusive results across the United States for all technologies.[136]

### Description of Confidence and Likelihood

Based on a large literature base (e.g., Holden et al. 2018;[87] Stephens et al. 2018[93]), there is *high confidence* that climate change and climate change–related amplification of disturbance effects have a negative impact on ecosystem resilience.

Studies based on different methodologies (including observational data analyses and numerical model experiments) are consistent in suggesting that agricultural intensification and/or irrigation cause cooling and the increase of precipitation and atmospheric humidity in the central US during summer; similar climate effects were found in fall and winter resulting from the increase of forest cover in the southeastern US due to agricultural abandonment. Increased flooding was observed in urbanized basins (e.g., Hodgkins et al. 2019[120]); elsewhere, there is no clear signal of increased flooding risks despite the strong increase in extreme precipitation (frequency and intensity). Based on this understanding, there is *high confidence* that climate and land-use change interact and that these interactions present challenges as well as opportunities for maintaining ecosystem resilience.

## Key Message 6.3

## Mitigation and Adaptation Priorities Will Increasingly Constrain Future Land-Use Options

### Description of Evidence Base

The evidence base describing Shared Socioeconomic Pathway (SSP) scenarios is large and well developed, having already been used in multiple international studies by the Intergovernmental Panel on Climate Change (e.g., IPCC 2022[180]) and the Coupled Model Intercomparison Project simulations. The "storylines" from the SSPs are developed by integrated assessment models (IAMs) into modeled projections of societal changes across multiple sectors. These scenarios provide alternative realizations of future societal pathways that are consistent with specified climate targets.[149,150] As such, they are useful for examining the range of possible challenges and changes facing our society over the rest of this century, although they do not provide predictions or probabilities of future trends.[198]

The Land-Use Harmonization 2 (LUH2) dataset provides a spatially explicit downscaling of the subset of SSP results used for the Scenario Model Intercomparison Project,[199] harmonizes them with historical land-use reconstructions, and provides a consistent data input for Earth system model simulations.[151] The LUH2 data provide global annual gridded (0.25° resolution) data of the fractional area occupied by 12 different land-use states, all transitions between those states, and land management data. The Land Change Monitoring, Assessment, and Projection (LCMAP) product described in the Introduction is a high-resolution annual land-cover dataset. That product complements the National Land Cover Database (NLCD),[200] which has greater thematic detail but is updated less frequently.

US agricultural land use in particular is tracked by a variety of surveys (e.g., the Census of Agriculture [CoA]) and longitudinal methods (e.g., the National Resources Inventory [NRI]), producing data that can be used to calibrate and validate the previously described remote sensing–based datasets.[8,137,201] Agricultural production is tracked through government statistics (e.g., the USDA National Agricultural Statistics Service), and crop yields are evaluated at finer spatial scales through crop insurance programs and combine yield monitors. The annual Inventory of US Greenhouse Gas Emissions and Sinks[55] estimates emissions from US land-use change, using agricultural area data from NRI and other sources.

Understanding of mitigation-driven land-use changes draws on the large IAM scenario evidence base described previously. Additionally, the Princeton Net-Zero America Project[172] is among the first to project where renewable electricity generation infrastructure might be sited at relatively fine spatial resolution.

## Major Uncertainties and Research Gaps

Although human land-use activities have historically resulted in a net source of carbon emissions to the atmosphere, there is considerable uncertainty in these, and future, estimates.[202]

The SSP scenarios and harmonized land-use datasets are generated with a global focus. Although they can be analyzed and used for specific regional and national impacts, they are not likely to have US-specific levels of detail. In addition, the national-to-regional focus of these scenarios prevents the consideration of many societal equity and justice issues. Inequality and governance are included as drivers of land-use change in the SSPs, where they are used primarily to address inequality between countries and regions.[203] The SSP datasets used by LUH2 were each produced by a single IAM; it is possible that alternative IAMs would represent land-use differently within each SSP, and those potential differences were not explored here. There are also very few studies that provide short-term predictive forecasts of national-level land-use changes over the next 1–2 decades.[204] SSP scenario analyses do not include climate feedbacks to the future scenarios, but other studies using coupled human–climate models[205] show that climate change is expected to modify the future land-use choices society is able to, or desires to, make.

Future agricultural land requirements will depend on various difficult-to-assess factors such as changing dietary preferences and climate change effects on crop yields. While IAM studies typically assume that historically observed rates of crop yield increase will continue into the future, more detailed modeling efforts such as the Agricultural Model Intercomparison Project (AgMIP)[156] suggest that climate-driven reductions in corn yield in the western US may be clearly observable in as little as two decades under pessimistic emissions scenarios (SSP5-8.5), for example. The potential of in situ adaptation practices (e.g., adoption of different crop varieties or planting dates) to mitigate the severity of climate-driven disruptions is an active area of study, but the literature base on climate-driven shifts in crop cultivation range is still very limited.[159] Studies show that dietary shifts away from animal products toward plant products have a large biophysical potential for reducing total agricultural land use and supporting natural ecosystem restoration and land-based mitigation.[165,167,168] The SSP scenarios cover a range of dietary shift assumptions, including a shift toward low-meat diets in SSP1 and associated market and trade implications.[150]

The efficacy of existing land-based mitigation measures is often debated. For example, estimates of the mitigation value of US corn ethanol production diverge significantly[187,188] depending on assumed counterfactual land use in the absence of ethanol production and the degree to which diversion of finite arable land might lead to unintended agricultural expansion elsewhere. While remote sensing provides an invaluable tool for tracking deforestation, it can struggle to differentiate more subtle land-use changes with similar land cover (for example, unmanaged native grasslands, rangeland, pastureland, hay land, cropland–pasture, idled cropland, and conservation reserves), making it difficult to distinguish between permanent agricultural expansion versus transient agricultural intensification.[206] This ambiguity contributes to the debate around the viability and desirability of wide-scale land-based mitigation and carbon dioxide removal (CDR) measures in future decarbonization scenarios.

## Description of Confidence and Likelihood

The land-use consequences of agricultural technology improvement (e.g., per-area crop yields, management intensity) and demand for land-based mitigation (including bioenergy and various CDR measures) are well explored in SSP scenario analyses.[150,205] Other collaborations (e.g., AgMIP) have explored the interaction between crop productivity and future climate change beyond what has been possible in integrated assessment modeling. Together, these literatures point to the influences of technology, mitigation needs, and climate change on land-use futures, hence the *high confidence* rating.

Primary data on cultivated cropland area and/or total cropland area are available via remote-sensing datasets (NLCD and LCMAP), longitudinal studies (NRI), and surveys (CoA). The longer-duration NRI and LCMAP datasets support a net decline in US cropland area over the last three and a half decades for which data are available, consistent with longer-term land-use records showing a mid-20th-century peak in US cropland area.[151] All four of these primary datasets are consistent with partial rebound of cropland area more recently, although with some disagreement around the starting year (as early as 2001 in NLCD or as late as 2012 in CoA) and magnitude of that rebound. Based on the agreement of these different primary data sources, there is *high confidence* of a long-term decline in US cropland area followed by a more recent rebound.

The LUH2 future scenarios all show stable or declining cropland use across the range of population growth and dietary shifts represented in the SSPs, although these scenario comparisons are not designed to represent the likelihood of different futures. Other literature suggests ongoing challenges in maintaining agricultural system resilience[155] in the face of a changing climate. Thus, continuation of the trend of declining land use is given a *medium confidence* rating, since there is not only evidence for multiple enabling preconditions but also key risks that are not captured in most scenario assessments.

The scenario assessment literature is consistent in identifying expanded electricity generation from renewable sources (i.e., wind and solar) and more widespread electrification of energy end use as preconditions for decarbonization of the energy sector.[171] This is consistent with recent trends of accelerating wind and energy deployment driven by the comparatively low cost of these energy sources, as well as policy support (e.g., through the Inflation Reduction Act), hence the *very likely*, *high confidence* rating. However, decarbonization scenarios have been widely criticized for over-reliance on land-intensive, technologically immature, or potentially unsustainable land-based mitigation and CDR measures,[207,208,209] and a variety of alternative scenarios that avoid land-intensive CDR have been developed.[190] Considering this, the statement about widespread land-use change for land-based mitigation is assigned a *low confidence* rating.

# References


1. Friis, C., J.Ø. Nielsen, I. Otero, H. Haberl, J. Niewöhner, and P. Hostert, 2016: From teleconnection to telecoupling: Taking stock of an emerging framework in land system science. *Journal of Land Use Science*, **11** (2), 131–153. https://doi.org/10.1080/1747423x.2015.1096423

2. Rindfuss, R.R., S.J. Walsh, B.L. Turner, J. Fox, and V. Mishra, 2004: Developing a science of land change: Challenges and methodological issues. *Proceedings of the National Academy of Sciences of the United States of America*, **101** (39), 13976–13981. https://doi.org/10.1073/pnas.0401545101

3. Turner, B.L., E.F. Lambin, and A. Reenberg, 2007: The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, **104** (52), 20666–20671. https://doi.org/10.1073/pnas.0704119104

4. Turner, B.L., E.F. Lambin, and P.H. Verburg, 2021: From land-use/land-cover to land system science. *Ambio*, **50** (7), 1291–1294. https://doi.org/10.1007/s13280-021-01510-4

5. Zhu, Z., S. Qiu, and S. Ye, 2022: Remote sensing of land change: A multifaceted perspective. *Remote Sensing of Environment*, **282**, 113266. https://doi.org/10.1016/j.rse.2022.113266

6. Dewitz, J. and USGS, 2021: National Land Cover Database (NLCD) 2019 Products. USGS data release (ver. 2.0, June 2021). U.S. Geological Survey. https://doi.org/10.5066/p9kzcm54

7. Jin, S., C. Homer, L. Yang, P. Danielson, J. Dewitz, C. Li, Z. Zhu, G. Xian, and D. Howard, 2019: Overall methodology design for the United States National Land cover database 2016 products. *Remote Sensing*, **11** (24), 2971. https://doi.org/10.3390/rs11242971

8. USGS, 2021: Land Change Monitoring, Assessment, and Projection (LCMAP) Collection 1.2 Science Products for the Conterminous United States: USGS Data Release. U.S. Geological Survey. https://doi.org/10.5066/p9sw95z0

9. Hamlington, B.D., A.S. Gardner, E. Ivins, J.T.M. Lenaerts, J.T. Reager, D.S. Trossman, E.D. Zaron, S. Adhikari, A. Arendt, A. Aschwanden, B.D. Beckley, D.P.S. Bekaert, G. Blewitt, L. Caron, D.P. Chambers, H.A. Chandanpurkar, K. Christianson, B. Csatho, R.I. Cullather, R.M. DeConto, J.T. Fasullo, T. Frederikse, J.T. Freymueller, D.M. Gilford, M. Girotto, W.C. Hammond, R. Hock, N. Holschuh, R.E. Kopp, F. Landerer, E. Larour, D. Menemenlis, M. Merrifield, J.X. Mitrovica, R.S. Nerem, I.J. Nias, V. Nieves, S. Nowicki, K. Pangaluru, C.G. Piecuch, R.D. Ray, D.R. Rounce, N.-J. Schlegel, H. Seroussi, M. Shirzaei, W.V. Sweet, I. Velicogna, N. Vinogradova, T. Wahl, D.N. Wiese, and M.J. Willis, 2020: Understanding of contemporary regional sea-level change and the implications for the future. *Reviews of Geophysics*, **58** (3), e2019RG000672. https://doi.org/10.1029/2019rg000672

10. Gariano, S.L. and F. Guzzetti, 2016: Landslides in a changing climate. *Earth-Science Reviews*, **162**, 227–252. https://doi.org/10.1016/j.earscirev.2016.08.011

11. Bessette-Kirton, E.K., J.A. Coe, W.H. Schulz, C. Cerovski-Darriau, and M.M. Einbund, 2020: Mobility characteristics of debris slides and flows triggered by Hurricane Maria in Puerto Rico. *Landslides*, **17** (12), 2795–2809. https://doi.org/10.1007/s10346-020-01445-z

12. Mathieson, W.L., P. Croft, and F.J. Wuttig, 2020: Infrastructure adaptions to changing permafrost conditions—Three case studies along the Trans Alaska Pipeline System. In: *Geo-Congress 2020*. Minneapolis, MN. American Society of Civil Engineers, 913–925. https://doi.org/10.1061/9780784482810.095

13. Patton, A.I., S.L. Rathburn, D.M. Capps, D. McGrath, and R.A. Brown, 2021: Ongoing landslide deformation in thawing permafrost. *Geophysical Research Letters*, **48** (16), e2021GL092959. https://doi.org/10.1029/2021gl092959

14. Coe, J.A., E.K. Bessette-Kirton, and M. Geertsema, 2018: Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery. *Landslides*, **15** (3), 393–407. https://doi.org/10.1007/s10346-017-0879-7

15. Dai, C., B. Higman, P.J. Lynett, M. Jacquemart, I.M. Howat, A.K. Liljedahl, A. Dufresne, J.T. Freymueller, M. Geertsema, M. Ward Jones, and P.J. Haeussler, 2020: Detection and assessment of a large and potentially tsunamigenic periglacial landslide in Barry Arm, Alaska. *Geophysical Research Letters*, **47** (22), e2020GL089800. https://doi.org/10.1029/2020gl089800

16. Higman, B., D.H. Shugar, C.P. Stark, G. Ekström, M.N. Koppes, P. Lynett, A. Dufresne, P.J. Haeussler, M. Geertsema, S. Gulick, A. Mattox, J.G. Venditti, M.A.L. Walton, N. McCall, E. McKittrick, B. MacInnes, E.L. Bilderback, H. Tang, M.J. Willis, B. Richmond, R.S. Reece, C. Larsen, B. Olson, J. Capra, A. Ayca, C. Bloom, H. Williams, D. Bonno, R. Weiss, A. Keen, V. Skanavis, and M. Loso, 2018: The 2015 landslide and tsunami in Taan Fiord, Alaska. *Scientific Reports*, **8** (1), 12993. https://doi.org/10.1038/s41598-018-30475-w

17. USGS, n.d.: Emergency Assessment of Post-Fire Debris-Flow Hazards. U.S. Geological Survey, accessed April 3, 2023. https://landslides.usgs.gov/hazards/postfire_debrisflow/

18. Goss, M., D.L. Swain, J.T. Abatzoglou, A. Sarhadi, C.A. Kolden, A.P. Williams, and N.S. Diffenbaugh, 2020: Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters*, **15** (9), 094016. https://doi.org/10.1088/1748-9326/ab83a7

19. Oakley, N.S., 2021: A warming climate adds complexity to post-fire hydrologic hazard planning. *Earth's Future*, **9** (7), e2021EF002149. https://doi.org/10.1029/2021ef002149

20. Parks, S.A. and J.T. Abatzoglou, 2020: Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters*, **47** (22), e2020GL089858. https://doi.org/10.1029/2020gl089858

21. Williams, A.P., J.T. Abatzoglou, A. Gershunov, J. Guzman-Morales, D.A. Bishop, J.K. Balch, and D.P. Lettenmaier, 2019: Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future*, **7** (8), 892–910. https://doi.org/10.1029/2019ef001210

22. Kean, J.W., D.M. Staley, J.T. Lancaster, F.K. Rengers, B.J. Swanson, J.A. Coe, J.L. Hernandez, A.J. Sigman, K.E. Allstadt, and D.N. Lindsay, 2019: Inundation, flow dynamics, and damage in the 9 January 2018 Montecito debris-flow event, California, USA: Opportunities and challenges for post-wildfire risk assessment. *Geosphere*, **15** (4), 1140–1163. https://doi.org/10.1130/ges02048.1

23. Lancaster, J.T., B.J. Swanson, S.G. Lukashov, N.S. Oakley, J.B. Lee, E.R. Spangler, J.L. Hernandez, B.P.E. Olson, M.J. DeFrisco, D.N. Lindsay, Y.J. Schwartz, S.E. McCrea, P.D. Roffers, and C.M. Tran, 2021: Observations and analyses of the 9 January 2018 debris-flow disaster, Santa Barbara County, California. *Environmental & Engineering Geoscience*, **27** (1), 3–27. https://doi.org/10.2113/eeg-d-20-00015

24. Murphy, S.F., R.B. McCleskey, D.A. Martin, J.H. Writer, and B.A. Ebel, 2018: Fire, flood, and drought: Extreme climate events alter flow paths and stream chemistry. *Journal of Geophysical Research: Biogeosciences*, **123** (8), 2513–2526. https://doi.org/10.1029/2017jg004349

25. Hallema, D.W., F.-N. Robinne, and K.D. Bladon, 2018: Reframing the challenge of global wildfire threats to water supplies. *Earth's Future*, **6** (6), 772–776. https://doi.org/10.1029/2018ef000867

26. Sankey, J.B., J. Kreitler, T.J. Hawbaker, J.L. McVay, M.E. Miller, E.R. Mueller, N.M. Vaillant, S.E. Lowe, and T.T. Sankey, 2017: Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophysical Research Letters*, **44** (17), 8884–8892. https://doi.org/10.1002/2017gl073979

27. Bhattachan, A., G.S. Okin, J. Zhang, S. Vimal, and D.P. Lettenmaier, 2019: Characterizing the role of wind and dust in traffic accidents in California. *GeoHealth*, **3** (10), 328–336. https://doi.org/10.1029/2019gh000212

28. Hand, J.L., W.H. White, K.A. Gebhart, N.P. Hyslop, T.E. Gill, and B.A. Schichtel, 2016: Earlier onset of the spring fine dust season in the southwestern United States. *Geophysical Research Letters*, **43** (8), 4001–4009. https://doi.org/10.1002/2016gl068519

29. Tong, D.Q., J.X.L. Wang, T.E. Gill, H. Lei, and B. Wang, 2017: Intensified dust storm activity and Valley fever infection in the southwestern United States. *Geophysical Research Letters*, **44** (9), 4304–4312. https://doi.org/10.1002/2017gl073524

30. Achakulwisut, P., S.C. Anenberg, J.E. Neumann, S.L. Penn, N. Weiss, A. Crimmins, N. Fann, J. Martinich, H. Roman, and L.J. Mickley, 2019: Effects of increasing aridity on ambient dust and public health in the U.S. Southwest under climate change. *GeoHealth*, **3** (5), 127–144. https://doi.org/10.1029/2019gh000187

31. Morman, S.A. and G.S. Plumlee, 2014: Ch. 15. Dust and human health. In: *Mineral Dust: A Key Player in the Earth System*. Knippertz, P. and J.-B.W. Stuut, Eds. Springer, Dordrecht, Netherlands, 385–409. https://doi.org/10.1007/978-94-017-8978-3_15

32. Marín, L., S.L. Forman, A. Valdez, and F. Bunch, 2005: Twentieth century dune migration at the Great Sand Dunes National Park and Preserve, Colorado, relation to drought variability. *Geomorphology*, **70** (1), 163–183. https://doi.org/10.1016/j.geomorph.2005.04.014

33. Redsteer, M.H., 2020: Ch. 8. Sand dunes, modern and ancient, on southern Colorado Plateau tribal lands, Southwestern USA. In: *Inland Dunes of North America*. Lancaster, N. and P. Hesp, Eds. Springer, Cham, Switzerland, 287–310. https://doi.org/10.1007/978-3-030-40498-7_8

34. Liu, Q., M. Yang, K. Mohammadi, D. Song, J. Bi, and G. Wang, 2022: Machine learning crop yield models based on meteorological features and comparison with a process-based model. *Artificial Intelligence for the Earth Systems*, **1** (4), e220002. https://doi.org/10.1175/aies-d-22-0002.1

35. Ortiz-Bobea, A., H. Wang, C.M. Carrillo, and T.R. Ault, 2019: Unpacking the climatic drivers of US agricultural yields. *Environmental Research Letters*, **14** (6), 064003. https://doi.org/10.1088/1748-9326/ab1e75

36. Lobell, D.B., J.M. Deines, and S.D. Tommaso, 2020: Changes in the drought sensitivity of US maize yields. *Nature Food*, **1** (11), 729–735. https://doi.org/10.1038/s43016-020-00165-w

37. Perry, E.D., J. Yu, and J. Tack, 2020: Using insurance data to quantify the multidimensional impacts of warming temperatures on yield risk. *Nature Communications*, **11** (1), 4542. https://doi.org/10.1038/s41467-020-17707-2

38. Li, Y., K. Guan, G.D. Schnitkey, E. DeLucia, and B. Peng, 2019: Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. *Global Change Biology*, **25** (7), 2325–2337. https://doi.org/10.1111/gcb.14628

39. Munson, S.M., J. Belnap, and G.S. Okin, 2011: Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau. *Proceedings of the National Academy of Sciences of the United States of America*, **108** (10), 3854–3859. https://doi.org/10.1073/pnas.1014947108

40. Phillips, M.L., B.E. McNellis, A. Howell, C.M. Lauria, J. Belnap, and S.C. Reed, 2022: Biocrusts mediate a new mechanism for land degradation under a changing climate. *Nature Climate Change*, **12** (1), 71–76. https://doi.org/10.1038/s41558-021-01249-6

41. Ravi, S., D.J. Law, J.S. Caplan, G.A. Barron-Gafford, K.M. Dontsova, J.F. Espeleta, J.C. Villegas, G.S. Okin, D.D. Breshears, and T.E. Huxman, 2022: Biological invasions and climate change amplify each other's effects on dryland degradation. *Global Change Biology*, **28** (1), 285–295. https://doi.org/10.1111/gcb.15919

42. Llopart, M., M.S. Reboita, E. Coppola, F. Giorgi, R.P. Da Rocha, and D.O. De Souza, 2018: Land use change over the Amazon forest and its impact on the local climate. *Water*, **10** (2), 149. https://doi.org/10.3390/w10020149

43. Guo, F., J. Lenoir, and T.C. Bonebrake, 2018: Land-use change interacts with climate to determine elevational species redistribution. *Nature Communications*, **9** (1), 1315. https://doi.org/10.1038/s41467-018-03786-9

44. Powers, R.P. and W. Jetz, 2019: Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios. *Nature Climate Change*, **9** (4), 323–329. https://doi.org/10.1038/s41558-019-0406-z

45. Rodríguez-Echeverry, J., C. Echeverría, C. Oyarzún, and L. Morales, 2018: Impact of land-use change on biodiversity and ecosystem services in the Chilean temperate forests. *Landscape Ecology*, **33** (3), 439–453. https://doi.org/10.1007/s10980-018-0612-5

46. Choi, Y., C.-H. Lim, H.I. Chung, Y. Kim, H.J. Cho, J. Hwang, F. Kraxner, G.S. Biging, W.-K. Lee, J. Chon, and S.W. Jeon, 2021: Forest management can mitigate negative impacts of climate and land-use change on plant biodiversity: Insights from the Republic of Korea. *Journal of Environmental Management*, **288**, 112400. https://doi.org/10.1016/j.jenvman.2021.112400

47. Lorenzen, M., Q. Orozco-Ramírez, R. Ramírez-Santiago, and G.G. Garza, 2020: Migration, socioeconomic transformation, and land-use change in Mexico's Mixteca Alta: Lessons for forest transition theory. *Land Use Policy*, **95**, 104580. https://doi.org/10.1016/j.landusepol.2020.104580

48. Sun, D., H. Yang, D. Guan, M. Yang, J. Wu, F. Yuan, C. Jin, A. Wang, and Y. Zhang, 2018: The effects of land use change on soil infiltration capacity in China: A meta-analysis. *Science of The Total Environment*, **626**, 1394–1401. https://doi.org/10.1016/j.scitotenv.2018.01.104

49. Harper, A.B., T. Powell, P.M. Cox, J. House, C. Huntingford, T.M. Lenton, S. Sitch, E. Burke, S.E. Chadburn, W.J. Collins, E. Comyn-Platt, V. Daioglou, J.C. Doelman, G. Hayman, E. Robertson, D. van Vuuren, A. Wiltshire, C.P. Webber, A. Bastos, L. Boysen, P. Ciais, N. Devaraju, A.K. Jain, A. Krause, B. Poulter, and S. Shu, 2018: Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature Communications*, **9** (1), 2938. https://doi.org/10.1038/s41467-018-05340-z

50. Zurqani, H.A., C.J. Post, E.A. Mikhailova, M.A. Schlautman, and J.L. Sharp, 2018: Geospatial analysis of land use change in the Savannah River Basin using Google Earth Engine. *International Journal of Applied Earth Observation and Geoinformation*, **69**, 175–185. https://doi.org/10.1016/j.jag.2017.12.006

51. Ciais, P., J. Tan, X. Wang, C. Roedenbeck, F. Chevallier, S.L. Piao, R. Moriarty, G. Broquet, C. Le Quéré, J.G. Canadell, S. Peng, B. Poulter, Z. Liu, and P. Tans, 2019: Five decades of northern land carbon uptake revealed by the interhemispheric $CO_2$ gradient. *Nature*, **568** (7751), 221–225. https://doi.org/10.1038/s41586-019-1078-6

52. Tagesson, T., G. Schurgers, S. Horion, P. Ciais, F. Tian, M. Brandt, A. Ahlström, J.-P. Wigneron, J. Ardö, S. Olin, L. Fan, Z. Wu, and R. Fensholt, 2020: Recent divergence in the contributions of tropical and boreal forests to the terrestrial carbon sink. *Nature Ecology & Evolution*, **4** (2), 202–209. https://doi.org/10.1038/s41559-019-1090-0

53. Bai, Y. and M.F. Cotrufo, 2022: Grassland soil carbon sequestration: Current understanding, challenges, and solutions. *Science*, **377** (6606), 603–608. https://doi.org/10.1126/science.abo2380

54. Bao, T., G. Jia, and X. Xu, 2023: Weakening greenhouse gas sink of pristine wetlands under warming. *Nature Climate Change*, **13**, 462–469. https://doi.org/10.1038/s41558-023-01637-0

55. EPA, 2022: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020. EPA 430-R-22-003. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020

56. Keenan, T.F. and C.A. Williams, 2018: The terrestrial carbon sink. *Annual Review of Environment and Resources*, **43** (1), 219–243. https://doi.org/10.1146/annurev-environ-102017-030204

57. Liu, Y., S. Piao, T. Gasser, P. Ciais, H. Yang, H. Wang, T.F. Keenan, M. Huang, S. Wan, J. Song, K. Wang, I.A. Janssens, J. Peñuelas, C. Huntingford, X. Wang, M. Altaf Arain, Y. Fang, J.B. Fisher, M. Huang, D.N. Huntzinger, A. Ito, A.K. Jain, J. Mao, A.M. Michalak, C. Peng, B. Poulter, C. Schwalm, X. Shi, H. Tian, Y. Wei, N. Zeng, Q. Zhu, and T. Wang, 2019: Field-experiment constraints on the enhancement of the terrestrial carbon sink by $CO_2$ fertilization. *Nature Geoscience*, **12** (10), 809–814. https://doi.org/10.1038/s41561-019-0436-1

58. Gerber, S., L.O. Hedin, S.G. Keel, S.W. Pacala, and E. Shevliakova, 2013: Land use change and nitrogen feedbacks constrain the trajectory of the land carbon sink. *Geophysical Research Letters*, **40** (19), 5218–5222. https://doi.org/10.1002/grl.50957

59. Pugh, T.A.M., M. Lindeskog, B. Smith, B. Poulter, A. Arneth, V. Haverd, and L. Calle, 2019: Role of forest regrowth in global carbon sink dynamics. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (10), 4382–4387. https://doi.org/10.1073/pnas.1810512116

60. Thom, D., W. Rammer, R. Garstenauer, and R. Seidl, 2018: Legacies of past land use have a stronger effect on forest carbon exchange than future climate change in a temperate forest landscape. *Biogeosciences*, **15** (18), 5699–5713. https://doi.org/10.5194/bg-15-5699-2018

61. Zhu, Z., S. Piao, T. Yan, P. Ciais, A. Bastos, X. Zhang, and Z. Wang, 2018: The accelerating land carbon sink of the 2000s may not be driven predominantly by the warming hiatus. *Geophysical Research Letters*, **45** (3), 1402–1409. https://doi.org/10.1002/2017gl075808

62. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

63. Redsteer, M.H., K.B. Kelley, H. Francis, and D. Block, 2018: Ch. 12. Accounts from tribal elders: Increasing vulnerability of the Navajo people to drought and climate change in the Southwestern United States. In: *Indigenous Knowledge for Climate Change Assessment and Adaptation*. Nakashima, D., I. Krupnik, and J.T. Rubis, Eds. Cambridge University Press, Cambridge, UK, 171–187. https://doi.org/10.1017/9781316481066.013

64. Irrgang, A.M., M. Bendixen, L.M. Farquharson, A.V. Baranskaya, L.H. Erikson, A.E. Gibbs, S.A. Ogorodov, P.P. Overduin, H. Lantuit, M.N. Grigoriev, and B.M. Jones, 2022: Drivers, dynamics and impacts of changing Arctic coasts. *Nature Reviews Earth & Environment*, **3** (1), 39–54. https://doi.org/10.1038/s43017-021-00232-1

65. UAFINE, 2019: Statewide Threat Assessment: Identification of Threats from Erosion, Flooding, and Thawing Permafrost in Remote Alaska Communities. Report #INE 19.03. University of Alaska Fairbanks, Institute of Northern Engineering. https://www.denali.gov/wp-content/uploads/2019/11/Statewide-Threat-Assessment-Final-Report-20-November-2019.pdf

66. Wenger, S.J., D.J. Isaak, C.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Elsner, B.E. Rieman, A.F. Hamlet, and J.E. Williams, 2011: Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **108** (34), 14175–14180. https://doi.org/10.1073/pnas.1103097108

67. Mote, P.W., J.T. Abatzoglou, K.D. Dello, K. Hegewisch, and D.E. Rupp, 2019: *Fourth Oregon Climate Assessment Report*. Oregon Climate Change Reserch Institute. https://www.oregon.gov/lcd/nh/documents/apx_9.1.21_or_climateassmtrpt4_2019_opt.pdf

68. Zhu, Z., J. Zhang, Z. Yang, A.H. Aljaddani, W.B. Cohen, S. Qiu, and C. Zhou, 2020: Continuous monitoring of land disturbance based on Landsat time series. *Remote Sensing of Environment*, **238**, 111116. https://doi.org/10.1016/j.rse.2019.03.009

69. Kelly, A.E. and M.L. Goulden, 2008: Rapid shifts in plant distribution with recent climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **105** (33), 11823–11826. https://doi.org/10.1073/pnas.0802891105

70. McCain, C.M., S.R.B. King, and T.M. Szewczyk, 2021: Unusually large upward shifts in cold-adapted, montane mammals as temperature warms. *Ecology*, **102** (4), e03300. https://doi.org/10.1002/ecy.3300

71. Piao, S., Q. Liu, A. Chen, I.A. Janssens, Y. Fu, J. Dai, L. Liu, X. Lian, M. Shen, and X. Zhu, 2019: Plant phenology and global climate change: Current progresses and challenges. *Global Change Biology*, **25** (6), 1922–1940. https://doi.org/10.1111/gcb.14619

72. Renner, S.S. and C.M. Zohner, 2018: Climate change and phenological mismatch in trophic interactions among plants, insects, and vertebrates. *Annual Review of Ecology, Evolution, and Systematics*, **49** (1), 165–182. https://doi.org/10.1146/annurev-ecolsys-110617-062535

73. Kirilenko, A.P. and R.A. Sedjo, 2007: Climate change impacts on forestry. *Proceedings of the National Academy of Sciences of the United States of America*, **104** (50), 19697–19702. https://doi.org/10.1073/pnas.0701424104

74. Malhi, G.S., M. Kaur, and P. Kaushik, 2021: Impact of climate change on agriculture and its mitigation strategies: A review. *Sustainability*, **13** (3), 1318. https://doi.org/10.3390/su13031318

75. White, H.J., P. Caplat, M.C. Emmerson, and J.M. Yearsley, 2021: Predicting future stability of ecosystem functioning under climate change. *Agriculture, Ecosystems & Environment*, **320**, 107600. https://doi.org/10.1016/j.agee.2021.107600

76. Keellings, D. and H. Moradkhani, 2020: Spatiotemporal evolution of heat wave severity and coverage across the United States. *Geophysical Research Letters*, **47** (9), e2020GL087097. https://doi.org/10.1029/2020gl087097

77. Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, J.T. Abatzoglou, K. Bolles, S.H. Baek, A.M. Badger, and B. Livneh, 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368** (6488), 314–318. https://doi.org/10.1126/science.aaz9600

78. Sun, Q., X. Zhang, F. Zwiers, S. Westra, and L.V. Alexander, 2021: A global, continental, and regional analysis of changes in extreme precipitation. *Journal of Climate*, **34** (1), 243–258. https://doi.org/10.1175/jcli-d-19-0892.1

79. Vu, T.M. and A.K. Mishra, 2019: Nonstationary frequency analysis of the recent extreme precipitation events in the United States. *Journal of Hydrology*, **575**, 999–1010. https://doi.org/10.1016/j.jhydrol.2019.05.090

80. Martin, J.T., G.T. Pederson, C.A. Woodhouse, E.R. Cook, G.J. McCabe, K.J. Anchukaitis, E.K. Wise, P.J. Erger, L. Dolan, M. McGuire, S. Gangopadhyay, K.J. Chase, J.S. Littell, S.T. Gray, S. St. George, J.M. Friedman, D.J. Sauchyn, J.-M. St-Jacques, and J. King, 2020: Increased drought severity tracks warming in the United States' largest river basin. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (21), 11328–11336. https://doi.org/10.1073/pnas.1916208117

81. Zhang, F., J.A. Biederman, M.P. Dannenberg, D. Yan, S.C. Reed, and W.K. Smith, 2021: Five decades of observed daily precipitation reveal longer and more variable drought events across much of the western United States. *Geophysical Research Letters*, **48** (7), e2020GL092293. https://doi.org/10.1029/2020gl092293

82. Peltier, D.M.P. and K. Ogle, 2019: Legacies of more frequent drought in ponderosa pine across the western United States. *Global Change Biology*, **25** (11), 3803–3816. https://doi.org/10.1111/gcb.14720

83. Chambers, J.C., C.R. Allen, and S.A. Cushman, 2019: Operationalizing ecological resilience concepts for managing species and ecosystems at risk. *Frontiers in Ecology and Evolution*, **7**, 241. https://doi.org/10.3389/fevo.2019.00241

84. North, M.P., R.E. Tompkins, A.A. Bernal, B.M. Collins, S.L. Stephens, and R.A. York, 2022: Operational resilience in western US frequent-fire forests. *Forest Ecology and Management*, **507**, 120004. https://doi.org/10.1016/j.foreco.2021.120004

85. Keesstra, S., J. Nunes, A. Novara, D. Finger, D. Avelar, Z. Kalantari, and A. Cerdà, 2018: The superior effect of nature based solutions in land management for enhancing ecosystem services. *Science of The Total Environment*, **610–611**, 997–1009. https://doi.org/10.1016/j.scitotenv.2017.08.077

86. Miner, K., L. Canavera, J. Gonet, K. Luis, M. Maddox, P. McCarney, G. Bridge, D. Schimel, and J. Rattlingleaf, 2023: The co-production of knowledge for climate science. *Nature Climate Change*, **13** (4), 307–308. https://doi.org/10.1038/s41558-023-01633-4

87. Holden, Z.A., A. Swanson, C.H. Luce, W.M. Jolly, M. Maneta, J.W. Oyler, D.A. Warren, R. Parsons, and D. Affleck, 2018: Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (36), E8349–E8357. https://doi.org/10.1073/pnas.1802316115

88. van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fulé, M.E. Harmon, A.J. Larson, J.M. Smith, A.H. Taylor, and T.T. Veblen, 2009: Widespread increase of tree mortality rates in the western United States. *Science*, **323** (5913), 521–524. https://doi.org/10.1126/science.1165000

89. Raffa, K.F., B.H. Aukema, B.J. Bentz, A.L. Carroll, J.A. Hicke, M.G. Turner, and W.H. Romme, 2008: Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of bark beetle eruptions. *BioScience*, **58** (6), 501–517. https://doi.org/10.1641/b580607

90. Stevens-Rumann, C.S., K.B. Kemp, P.E. Higuera, B.J. Harvey, M.T. Rother, D.C. Donato, P. Morgan, and T.T. Veblen, 2018: Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters*, **21** (2), 243–252. https://doi.org/10.1111/ele.12889

91. Williams, A.P., C.D. Allen, C.I. Millar, T.W. Swetnam, J. Michaelsen, C.J. Still, and S.W. Leavitt, 2010: Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the National Academy of Sciences of the United States of America*, **107** (50), 21289–21294. https://doi.org/10.1073/pnas.0914211107

92. Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.-H. Lim, G. Allard, S.W. Running, A. Semerci, and N. Cobb, 2010: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, **259** (4), 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

93. Stephens, S.L., B.M. Collins, C.J. Fettig, M.A. Finney, C.M. Hoffman, E.E. Knapp, M.P. North, H. Safford, and R.B. Wayman, 2018: Drought, tree mortality, and wildfire in forests adapted to frequent fire. *BioScience*, **68** (2), 77–88. https://doi.org/10.1093/biosci/bix146

94. Archer, S.R., E.M. Andersen, K.I. Predick, S. Schwinning, R.J. Steidl, and S.R. Woods, 2017: Ch. 2. Woody plant encroachment: Causes and consequences. In: *Rangeland Systems: Processes, Management and Challenges*. Briske, D.D., Ed. Springer, Cham, Switzerland, 25–84. https://doi.org/10.1007/978-3-319-46709-2_2

95. Yu, K., G.S. Okin, S. Ravi, and P. D'Odorico, 2016: Potential of grass invasions in desert shrublands to create novel ecosystem states under variable climate. *Ecohydrology*, **9** (8), 1496–1506. https://doi.org/10.1002/eco.1742

96. Bradley, B.A., C.A. Curtis, E.J. Fusco, J.T. Abatzoglou, J.K. Balch, S. Dadashi, and M.-N. Tuanmu, 2018: Cheatgrass (*Bromus tectorum*) distribution in the intermountain Western United States and its relationship to fire frequency, seasonality, and ignitions. *Biological Invasions*, **20** (6), 1493–1506. https://doi.org/10.1007/s10530-017-1641-8

97. Reeves, M.C. and J.E. Mitchell, 2012: A Synoptic Review of U.S. Rangelands: A Technical Document Supporting the Forest Service 2010 RPA Assessment. Gen. Tech. Rep. RMRS-GTR-288. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 128 pp. https://doi.org/10.2737/rmrs-gtr-288

98. Xu, S., N. Eisenhauer, A.F.A. Pellegrini, J. Wang, G. Certini, C.A. Guerra, and D.Y.F. Lai, 2022: Fire frequency and type regulate the response of soil carbon cycling and storage to fire across soil depths and ecosystems: A meta-analysis. *Science of The Total Environment*, **825**, 153921. https://doi.org/10.1016/j.scitotenv.2022.153921

99. Johnstone, J.F., T.N. Hollingsworth, F.S. Chapin III, and M.C. Mack, 2010: Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. *Global Change Biology*, **16** (4), 1281–1295. https://doi.org/10.1111/j.1365-2486.2009.02051.x

100. Kettridge, N., M.R. Turetsky, J.H. Sherwood, D.K. Thompson, C.A. Miller, B.W. Benscoter, M.D. Flannigan, B.M. Wotton, and J.M. Waddington, 2015: Moderate drop in water table increases peatland vulnerability to post-fire regime shift. *Scientific Reports*, **5** (1), 8063. https://doi.org/10.1038/srep08063

101. Peng, X., T. Zhang, O.W. Frauenfeld, S. Wang, L. Qiao, R. Du, and C. Mu, 2020: Northern Hemisphere Greening in association with warming permafrost. *Journal of Geophysical Research: Biogeosciences*, **125** (1), e2019JG005086. https://doi.org/10.1029/2019jg005086

102. Williams, C.A., H. Gu, and T. Jiao, 2021: Climate impacts of U.S. forest loss span net warming to net cooling. *Science Advances*, **7** (7), 8859. https://doi.org/10.1126/sciadv.aax8859

103. Jiang, Y., G. Wang, W. Liu, A. Erfanian, Q. Peng, and R. Fu, 2021: Modeled response of South American climate to three decades of deforestation. *Journal of Climate*, **34** (6), 2189–2203. https://doi.org/10.1175/jcli-d-20-0380.1

104. Wang, G., M. Yu, and Y. Xue, 2016: Modeling the potential contribution of land cover changes to the late twentieth century Sahel drought using a regional climate model: Impact of lateral boundary conditions. *Climate Dynamics*, **47** (11), 3457–3477. https://doi.org/10.1007/s00382-015-2812-x

105. Alkama, R. and A. Cescatti, 2016: Biophysical climate impacts of recent changes in global forest cover. *Science*, **351** (6273), 600–604. https://doi.org/10.1126/science.aac8083

106. Li, Y., Y. Liu, G. Bohrer, Y. Cai, A. Wilson, T. Hu, Z. Wang, and K. Zhao, 2022: Impacts of forest loss on local climate across the conterminous United States: Evidence from satellite time-series observations. *Science of The Total Environment*, **802**, 149651. https://doi.org/10.1016/j.scitotenv.2021.149651

107. Mykleby, P.M., P.K. Snyder, and T.E. Twine, 2017: Quantifying the trade-off between carbon sequestration and albedo in midlatitude and high-latitude North American forests. *Geophysical Research Letters*, **44** (5), 2493–2501. https://doi.org/10.1002/2016GL071459

108. Ellenburg, W.L., R.T. McNider, J.F. Cruise, and J.R. Christy, 2016: Towards an understanding of the twentieth-century cooling trend in the southeastern United States: Biogeophysical impacts of land-use change. *Earth Interactions*, **20** (18), 1–31. https://doi.org/10.1175/ei-d-15-0038.1

109. Seto, K.C., A. Reenberg, C.G. Boone, M. Fragkias, D. Haase, T. Langanke, P. Marcotullio, D.K. Munroe, B. Olah, and D. Simon, 2012: Urban land teleconnections and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (20), 7687–7692. https://doi.org/10.1073/pnas.1117622109

110. McWethy, D.B., T. Schoennagel, P.E. Higuera, M. Krawchuk, B.J. Harvey, E.C. Metcalf, C. Schultz, C. Miller, A.L. Metcalf, B. Buma, A. Virapongse, J.C. Kulig, R.C. Stedman, Z. Ratajczak, C.R. Nelson, and C. Kolden, 2019: Rethinking resilience to wildfire. *Nature Sustainability*, **2** (9), 797–804. https://doi.org/10.1038/s41893-019-0353-8

111. Sohn, J.A., S. Saha, and J. Bauhus, 2016: Potential of forest thinning to mitigate drought stress: A meta-analysis. *Forest Ecology and Management*, **380**, 261–273. https://doi.org/10.1016/j.foreco.2016.07.046

112. Oliver, T.H. and M.D. Morecroft, 2014: Interactions between climate change and land use change on biodiversity: Attribution problems, risks, and opportunities. *WIREs Climate Change*, **5** (3), 317–335. https://doi.org/10.1002/wcc.271

113. Li, C., L.M. Fultz, J. Moore-Kucera, V. Acosta-Martínez, J. Horita, R. Strauss, J. Zak, F. Calderón, and D. Weindorf, 2017: Soil carbon sequestration potential in semi-arid grasslands in the Conservation Reserve Program. *Geoderma*, **294**, 80–90. https://doi.org/10.1016/j.geoderma.2017.01.032

114. Misebo, A.M., M. Pietrzykowski, and B. Woś, 2022: Soil carbon sequestration in novel ecosystems at post-mine sites—A new insight into the determination of key factors in the restoration of terrestrial ecosystems. *Forests*, **13** (1). https://doi.org/10.3390/f13010063

115. North, M.P. and M.D. Hurteau, 2011: High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest. *Forest Ecology and Management*, **261** (6), 1115–1120. https://doi.org/10.1016/j.foreco.2010.12.039

116. Auch, R.F., D.F. Wellington, J.L. Taylor, S.V. Stehman, H.J. Tollerud, J.F. Brown, T.R. Loveland, B.W. Pengra, J.A. Horton, Z. Zhu, A.A. Midekisa, K.L. Sayler, G. Xian, C.P. Barber, and R.R. Reker, 2022: Conterminous United States land-cover change (1985–2016): New insights from annual time series. *Land*, **11** (2). https://doi.org/10.3390/land11020298

117. Wright, D.B., C.D. Bosma, and T. Lopez-Cantu, 2019: U.S. hydrologic design standards insufficient due to large increases in frequency of rainfall extremes. *Geophysical Research Letters*, **46** (14), 8144–8153. https://doi.org/10.1029/2019gl083235

118. Collins, M.J., G.A. Hodgkins, S.A. Archfield, and R.M. Hirsch, 2022: The occurrence of large floods in the United States in the modern hydroclimate regime: Seasonality, trends, and large-scale climate associations. *Water Resources Research*, **58** (2), e2021WR030480. https://doi.org/10.1029/2021wr030480

119. Debbage, N. and J.M. Shepherd, 2018: The influence of urban development patterns on streamflow characteristics in the Charlanta Megaregion. *Water Resources Research*, **54** (5), 3728–3747. https://doi.org/10.1029/2017wr021594

120. Hodgkins, G.A., R.W. Dudley, S.A. Archfield, and B. Renard, 2019: Effects of climate, regulation, and urbanization on historical flood trends in the United States. *Journal of Hydrology*, **573**, 697–709. https://doi.org/10.1016/j.jhydrol.2019.03.102

121. Debbage, N. and J.M. Shepherd, 2019: Urban influences on the spatiotemporal characteristics of runoff and precipitation during the 2009 Atlanta flood. *Journal of Hydrometeorology*, **20** (1), 3–21. https://doi.org/10.1175/jhm-d-18-0010.1

122. Fan, J., Y. Zhang, Z. Li, J. Hu, and D. Rosenfeld, 2020: Urbanization-induced land and aerosol impacts on sea-breeze circulation and convective precipitation. *Atmospheric Chemistry and Physics*, **20**, 14163–14182. https://doi.org/10.5194/acp-20-14163-2020

123. Niyogi, D., M. Lei, C. Kishtawal, P. Schmid, and M. Shepherd, 2017: Urbanization impacts on the summer heavy rainfall climatology over the eastern United States. *Earth Interactions*, **21** (5), 1–17. https://doi.org/10.1175/ei-d-15-0045.1

124. Zhang, W., G. Villarini, G.A. Vecchi, and J.A. Smith, 2018: Urbanization exacerbated the rainfall and flooding caused by Hurricane Harvey in Houston. *Nature*, **563** (7731), 384–388. https://doi.org/10.1038/s41586-018-0676-z

125. Baguskas, S.A., R.E.S. Clemesha, and M.E. Loik, 2018: Coastal low cloudiness and fog enhance crop water use efficiency in a California agricultural system. *Agricultural and Forest Meteorology*, **252**, 109–120. https://doi.org/10.1016/j.agrformet.2018.01.015

126. Williams, A.P., P. Gentine, M.A. Moritz, D.A. Roberts, and J.T. Abatzoglou, 2018: Effect of reduced summer cloud shading on evaporative demand and wildfire in coastal Southern California. *Geophysical Research Letters*, **45** (11), 5653–5662. https://doi.org/10.1029/2018gl077319

127. Paschalis, A., T. Chakraborty, S. Fatichi, N. Meili, and G. Manoli, 2021: Urban forests as main regulator of the evaporative cooling effect in cities. *AGU Advances*, **2** (2), e2020AV000303. https://doi.org/10.1029/2020av000303

128. Winbourne, J.B., T.S. Jones, S.M. Garvey, J.L. Harrison, L. Wang, D. Li, P.H. Templer, and L.R. Hutyra, 2020: Tree transpiration and urban temperatures: Current understanding, implications, and future research directions. *BioScience*, **70** (7), 576–588. https://doi.org/10.1093/biosci/biaa055

129. Zhang, Z., A. Paschalis, and A. Mijic, 2021: Planning London's green spaces in an integrated water management approach to enhance future resilience in urban stormwater control. *Journal of Hydrology*, **597**, 126126. https://doi.org/10.1016/j.jhydrol.2021.126126

130. Hardiman, B.S., J.A. Wang, L.R. Hutyra, C.K. Gately, J.M. Getson, and M.A. Friedl, 2017: Accounting for urban biogenic fluxes in regional carbon budgets. *Science of The Total Environment*, **592**, 366–372. https://doi.org/10.1016/j.scitotenv.2017.03.028

131. Miller, J.B., S.J. Lehman, K.R. Verhulst, C.E. Miller, R.M. Duren, V. Yadav, S. Newman, and C.D. Sloop, 2020: Large and seasonally varying biospheric $CO_2$ fluxes in the Los Angeles megacity revealed by atmospheric radiocarbon. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (43), 26681–26687. https://doi.org/10.1073/pnas.2005253117

132. Wei, D., A. Reinmann, L.D. Schiferl, and R. Commane, 2022: High resolution modeling of vegetation reveals large summertime biogenic $CO_2$ fluxes in New York City. *Environmental Research Letters*, **17** (12), 124031. https://doi.org/10.1088/1748-9326/aca68f

133. Payen, F.T., D.L. Evans, N. Falagán, C.A. Hardman, S. Kourmpetli, L. Liu, R. Marshall, B.R. Mead, and J.A.C. Davies, 2022: How much food can we grow in urban areas? Food production and crop yields of urban agriculture: A meta-analysis. *Earth's Future*, **10** (8), e2022EF002748. https://doi.org/10.1029/2022ef002748

134. Allred, B.W., W.K. Smith, D. Twidwell, J.H. Haggerty, S.W. Running, D.E. Naugle, and S.D. Fuhlendorf, 2015: Ecosystem services lost to oil and gas in North America. *Science*, **348** (6233), 401–402. https://doi.org/10.1126/science.aaa4785

135. Rottler, C.M., I.C. Burke, K.A. Palmquist, J.B. Bradford, and W.K. Lauenroth, 2018: Current reclamation practices after oil and gas development do not speed up succession or plant community recovery in big sagebrush ecosystems in Wyoming. *Restoration Ecology*, **26** (1), 114–123. https://doi.org/10.1111/rec.12543

136. Solaun, K. and E. Cerdá, 2019: Climate change impacts on renewable energy generation. A review of quantitative projections. *Renewable and Sustainable Energy Reviews*, **116**, 109415. https://doi.org/10.1016/j.rser.2019.109415

137. Lark, T.J., S.A. Spawn, M. Bougie, and H.K. Gibbs, 2020: Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nature Communications*, **11** (1), 4295. https://doi.org/10.1038/s41467-020-18045-z

138. Lark, T.J., J.M. Salmon, and H.K. Gibbs, 2015: Cropland expansion outpaces agricultural and biofuel policies in the United States. *Environmental Research Letters*, **10** (4), 044003. https://doi.org/10.1088/1748-9326/10/4/044003

139. Liu, J., V. Hull, M. Batistella, R. DeFries, T. Dietz, F. Fu, T.W. Hertel, R.C. Izaurralde, E.F. Lambin, S. Li, L.A. Martinelli, W.J. McConnell, E.F. Moran, R. Naylor, Z. Ouyang, K.R. Polenske, A. Reenberg, G. de Miranda Rocha, C.S. Simmons, P.H. Verburg, P.M. Vitousek, F. Zhang, and C. Zhu, 2013: Framing sustainability in a telecoupled world. *Ecology and Society*, **18** (2). http://www.jstor.org/stable/26269331

140. Wimberly, M.C., D.M. Narem, P.J. Bauman, B.T. Carlson, and M.A. Ahlering, 2018: Grassland connectivity in fragmented agricultural landscapes of the north-central United States. *Biological Conservation*, **217**, 121–130. https://doi.org/10.1016/j.biocon.2017.10.031

141. Spawn, S.A., T.J. Lark, and H.K. Gibbs, 2019: Carbon emissions from cropland expansion in the United States. *Environmental Research Letters*, **14** (4), 045009. https://doi.org/10.1088/1748-9326/ab0399

142. Isbell, F., D. Tilman, P.B. Reich, and A.T. Clark, 2019: Deficits of biodiversity and productivity linger a century after agricultural abandonment. *Nature Ecology & Evolution*, **3** (11), 1533–1538. https://doi.org/10.1038/s41559-019-1012-1

143. Yang, Y., D. Tilman, G. Furey, and C. Lehman, 2019: Soil carbon sequestration accelerated by restoration of grassland biodiversity. *Nature Communications*, **10** (1), 718. https://doi.org/10.1038/s41467-019-08636-w

144. Chen, L. and P.A. Dirmeyer, 2017: Impacts of land-use/land-cover change on afternoon precipitation over North America. *Journal of Climate*, **30** (6), 2121–2140. https://doi.org/10.1175/jcli-d-16-0589.1

145. Alter, R.E., H.C. Douglas, J.M. Winter, and E.A.B. Eltahir, 2018: Twentieth century regional climate change during the summer in the central United States attributed to agricultural intensification. *Geophysical Research Letters*, **45** (3), 1586–1594. https://doi.org/10.1002/2017gl075604

146. Mueller, N.D., E.E. Butler, K.A. McKinnon, A. Rhines, M. Tingley, N.M. Holbrook, and P. Huybers, 2016: Cooling of US Midwest summer temperature extremes from cropland intensification. *Nature Climate Change*, **6** (3), 317–322. https://doi.org/10.1038/nclimate2825

147. Mueller, N.D., A. Rhines, E.E. Butler, D.K. Ray, S. Siebert, N.M. Holbrook, and P. Huybers, 2017: Global relationships between cropland intensification and summer temperature extremes over the last 50 years. *Journal of Climate*, **30** (18), 7505–7528. https://doi.org/10.1175/jcli-d-17-0096.1

148. Yang, Z., Y. Qian, Y. Liu, L.K. Berg, H. Hu, F. Dominguez, B. Yang, Z. Feng, W.I. Gustafson Jr, M. Huang, and Q. Tang, 2019: Irrigation impact on water and energy cycle during dry years over the United States using convection-permitting WRF and a dynamical recycling model. *Journal of Geophysical Research: Atmospheres*, **124** (21), 11220–11241. https://doi.org/10.1029/2019jd030524

149. O'Neill, B.C., E. Kriegler, K.L. Ebi, E. Kemp-Benedict, K. Riahi, D.S. Rothman, B.J. van Ruijven, D.P. van Vuuren, J. Birkmann, K. Kok, M. Levy, and W. Solecki, 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

150. Popp, A., K. Calvin, S. Fujimori, P. Havlik, F. Humpenöder, E. Stehfest, B.L. Bodirsky, J.P. Dietrich, J.C. Doelmann, M. Gusti, T. Hasegawa, P. Kyle, M. Obersteiner, A. Tabeau, K. Takahashi, H. Valin, S. Waldhoff, I. Weindl, M. Wise, E. Kriegler, H. Lotze-Campen, O. Fricko, K. Riahi, and D.P. van Vuuren, 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42**, 331–345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

151. Hurtt, G.C., L. Chini, R. Sahajpal, S. Frolking, B.L. Bodirsky, K. Calvin, J.C. Doelman, J. Fisk, S. Fujimori, K. Klein Goldewijk, T. Hasegawa, P. Havlik, A. Heinimann, F. Humpenöder, J. Jungclaus, J.O. Kaplan, J. Kennedy, T. Krisztin, D. Lawrence, P. Lawrence, L. Ma, O. Mertz, J. Pongratz, A. Popp, B. Poulter, K. Riahi, E. Shevliakova, E. Stehfest, P. Thornton, F.N. Tubiello, D.P. van Vuuren, and X. Zhang, 2020: Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6. *Geoscientific Model Development*, **13** (11), 5425–5464. https://doi.org/10.5194/gmd-13-5425-2020

152. Richter, S.M. and R.P. Bixler, 2022: Complexifying urban expansion: An exploratory, gradient-based approach. *Buildings and Cities*, **3** (1), 792–807. https://doi.org/10.5334/bc.226

153. Chen, G., X. Li, X. Liu, Y. Chen, X. Liang, J. Leng, X. Xu, W. Liao, Y.a. Qiu, Q. Wu, and K. Huang, 2020: Global projections of future urban land expansion under shared socioeconomic pathways. *Nature Communications*, **11** (1), 537. https://doi.org/10.1038/s41467-020-14386-x

154. Lobell, D.B., M.J. Roberts, W. Schlenker, N. Braun, B.B. Little, R.M. Rejesus, and G.L. Hammer, 2014: Greater sensitivity to drought accompanies maize yield increase in the U.S. Midwest. *Science*, **344** (6183), 516–519. https://doi.org/10.1126/science.1251423

155. Ortiz-Bobea, A., T.R. Ault, C.M. Carrillo, R.G. Chambers, and D.B. Lobell, 2021: Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change*, **11** (4), 306–312. https://doi.org/10.1038/s41558-021-01000-1

156. Jägermeyr, J., C. Müller, A.C. Ruane, J. Elliott, J. Balkovic, O. Castillo, B. Faye, I. Foster, C. Folberth, J.A. Franke, K. Fuchs, J.R. Guarin, J. Heinke, G. Hoogenboom, T. Iizumi, A.K. Jain, D. Kelly, N. Khabarov, S. Lange, T.-S. Lin, W. Liu, O. Mialyk, S. Minoli, E.J. Moyer, M. Okada, M. Phillips, C. Porter, S.S. Rabin, C. Scheer, J.M. Schneider, J.F. Schyns, R. Skalsky, A. Smerald, T. Stella, H. Stephens, H. Webber, F. Zabel, and C. Rosenzweig, 2021: Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food*, **2** (11), 873–885. https://doi.org/10.1038/s43016-021-00400-y

157. Abramoff, R.Z., P. Ciais, P. Zhu, T. Hasegawa, H. Wakatsuki, and D. Makowski, 2023: Adaptation strategies strongly reduce the future impacts of climate change on simulated crop yields. *Earth's Future*, **11** (4), e2022EF003190. https://doi.org/10.1029/2022ef003190

158. Minoli, S., C. Müller, J. Elliott, A.C. Ruane, J. Jägermeyr, F. Zabel, M. Dury, C. Folberth, L. François, T. Hank, I. Jacquemin, W. Liu, S. Olin, and T.A.M. Pugh, 2019: Global response patterns of major rainfed crops to adaptation by maintaining current growing periods and irrigation. *Earth's Future*, **7** (12), 1464–1480. https://doi.org/10.1029/2018ef001130

159. Sloat, L.L., S.J. Davis, J.S. Gerber, F.C. Moore, D.K. Ray, P.C. West, and N.D. Mueller, 2020: Climate adaptation by crop migration. *Nature Communications*, **11** (1), 1243. https://doi.org/10.1038/s41467-020-15076-4

160. Diffenbaugh, N.S., F.V. Davenport, and M. Burke, 2021: Historical warming has increased U.S. crop insurance losses. *Environmental Research Letters*, **16** (8), 084025. https://doi.org/10.1088/1748-9326/ac1223

161. McCarl, B.A., A.W. Thayer, and J.P.H. Jones, 2016: The challenge of climate change adaptation for agriculture: An economically oriented review. *Journal of Agricultural and Applied Economics*, **48** (4), 321–344. https://doi.org/10.1017/aae.2016.27

162. Bradford, J.B., D.R. Schlaepfer, W.K. Lauenroth, C.B. Yackulic, M. Duniway, S. Hall, G. Jia, K. Jamiyansharav, S.M. Munson, S.D. Wilson, and B. Tietjen, 2017: Future soil moisture and temperature extremes imply expanding suitability for rainfed agriculture in temperate drylands. *Scientific Reports*, **7** (1), 12923. https://doi.org/10.1038/s41598-017-13165-x

163. Seifert, C.A. and D.B. Lobell, 2015: Response of double cropping suitability to climate change in the United States. *Environmental Research Letters*, **10** (2), 024002. https://doi.org/10.1088/1748-9326/10/2/024002

164. Shepon, A., G. Eshel, E. Noor, and R. Milo, 2018: The opportunity cost of animal based diets exceeds all food losses. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (15), 3804–3809. https://doi.org/10.1073/pnas.1713820115

165. Rizvi, S., C. Pagnutti, E. Fraser, C.T. Bauch, and M. Anand, 2018: Global land use implications of dietary trends. *PLoS ONE*, **13** (8), e0200781. https://doi.org/10.1371/journal.pone.0200781

166. Rubio, N.R., N. Xiang, and D.L. Kaplan, 2020: Plant-based and cell-based approaches to meat production. *Nature Communications*, **11** (1), 6276. https://doi.org/10.1038/s41467-020-20061-y

167. Hayek, M.N., H. Harwatt, W.J. Ripple, and N.D. Mueller, 2021: The carbon opportunity cost of animal-sourced food production on land. *Nature Sustainability*, **4** (1), 21–24. https://doi.org/10.1038/s41893-020-00603-4

168. Sun, Z., L. Scherer, A. Tukker, S.A. Spawn-Lee, M. Bruckner, H.K. Gibbs, and P. Behrens, 2022: Dietary change in high-income nations alone can lead to substantial double climate dividend. *Nature Food*, **3** (1), 29–37. https://doi.org/10.1038/s43016-021-00431-5

169. Principato, L., L. Secondi, C. Cicatiello, and G. Mattia, 2020: Caring more about food: The unexpected positive effect of the COVID-19 lockdown on household food management and waste. *Socio-Economic Planning Sciences*, **82**, 100953. https://doi.org/10.1016/j.seps.2020.100953

170. Roe, B.E., K. Bender, and D. Qi, 2021: The impact of COVID-19 on consumer food waste. *Applied Economic Perspectives and Policy*, **43** (1), 401–411. https://doi.org/10.1002/aepp.13079

171. Azevedo, I., C. Bataille, J. Bistline, L. Clarke, and S. Davis, 2021: Net-zero emissions energy systems: What we know and do not know. *Energy and Climate Change*, **2**, 100049. https://doi.org/10.1016/j.egycc.2021.100049

172. Larson, E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, E. Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan, 2021: Final Report Summary—Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Princeton University, Princeton, NJ. https://netzeroamerica.princeton.edu/the-report

173. Bessette, D.L. and S.B. Mills, 2021: Farmers vs. lakers: Agriculture, amenity, and community in predicting opposition to United States wind energy development. *Energy Research & Social Science*, **72**, 101873. https://doi.org/10.1016/j.erss.2020.101873

174. Lovering, J., M. Swain, L. Blomqvist, and R.R. Hernandez, 2022: Land-use intensity of electricity production and tomorrow's energy landscape. *PLoS ONE*, **17** (7), e0270155. https://doi.org/10.1371/journal.pone.0270155

175. Barron-Gafford, G.A., M.A. Pavao-Zuckerman, R.L. Minor, L.F. Sutter, I. Barnett-Moreno, D.T. Blackett, M. Thompson, K. Dimond, A.K. Gerlak, G.P. Nabhan, and J.E. Macknick, 2019: Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nature Sustainability*, **2** (9), 848–855. https://doi.org/10.1038/s41893-019-0364-5

176. Sovacool, B.K., S.H. Ali, M. Bazilian, B. Radley, B. Nemery, J. Okatz, and D. Mulvaney, 2020: Sustainable minerals and metals for a low-carbon future. *Science*, **367** (6437), 30–33. https://doi.org/10.1126/science.aaz6003

177. Graham, J.D., J.A. Rupp, and E. Brungard, 2021: Lithium in the green energy transition: The quest for both sustainability and security. *Sustainability*, **13** (20), 11274. https://doi.org/10.3390/su132011274

178. Canadell, J.G. and E.D. Schulze, 2014: Global potential of biospheric carbon management for climate mitigation. *Nature Communications*, **5** (1), 5282. https://doi.org/10.1038/ncomms6282

179. DOS and EOP, 2021: The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. U.S. Department of State and U.S. Executive Office of the President, Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2021/10/us-long-term-strategy.pdf

180. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.001

181. Turner, P.A., C.B. Field, D.B. Lobell, D.L. Sanchez, and K.J. Mach, 2018: Unprecedented rates of land-use transformation in modelled climate change mitigation pathways. *Nature Sustainability*, **1** (5), 240–245. https://doi.org/10.1038/s41893-018-0063-7

182. Khanna, M., L. Chen, B. Basso, X. Cai, J.L. Field, K. Guan, C. Jiang, T.J. Lark, T.L. Richard, S.A. Spawn-Lee, P. Yang, and K.Y. Zipp, 2021: Redefining marginal land for bioenergy crop production. *GCB Bioenergy*, **13** (10), 1590–1609. https://doi.org/10.1111/gcbb.12877

183. The White House, 2016: United States Mid-Century Strategy for Deep Decarbonization. The White House, Washington, DC, 110 pp. https://obamawhitehouse.archives.gov/sites/default/files/docs/mid_century_strategy_report-final.pdf

184. Qin, Z., J.B. Dunn, H. Kwon, S. Mueller, and M.M. Wander, 2016: Soil carbon sequestration and land use change associated with biofuel production: Empirical evidence. *GCB Bioenergy*, **8** (1), 66–80. https://doi.org/10.1111/gcbb.12237

185. Amundson, R., 2022: The Pandora's box of soil carbon. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (11), e2201077119. https://doi.org/10.1073/pnas.2201077119

186. Anderson-Teixeira, K.J. and E.P. Belair, 2022: Effective forest-based climate change mitigation requires our best science. *Global Change Biology*, **28** (4), 1200–1203. https://doi.org/10.1111/gcb.16008

187. Lark, T.J., N.P. Hendricks, A. Smith, N. Pates, S.A. Spawn-Lee, M. Bougie, E.G. Booth, C.J. Kucharik, and H.K. Gibbs, 2022: Environmental outcomes of the US renewable fuel standard. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (9), e2101084119. https://doi.org/10.1073/pnas.2101084119

188. Lee, U., H. Kwon, M. Wu, and M. Wang, 2021: Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: Implications for greenhouse gas emission reductions. *Biofuels, Bioproducts and Biorefining*, **15** (5), 1318–1331. https://doi.org/10.1002/bbb.2225

189. Smith, S., O. Geden, G.F. Nemet, M. Gidden, W.F. Lamb, C. Powis, R. Bellamy, M. Callaghan, A. Cowie, E. Cox, S. Fuss, T. Gasser, G. Grassi, J. Greene, S. Lueck, A. Mohan, F. Müller-Hansen, G. Peters, Y. Pratama, T. Repke, K. Riahi, F. Schenuit, J. Steinhauser, J. Strefler, J.M. Valenzuela, and J. Minx, 2023: State of Carbon Dioxide Removal—1st Edition. OSF. https://doi.org/10.17605/osf.io/w3b4z

190. van Vuuren, D.P., E. Stehfest, D.E.H.J. Gernaat, M. van den Berg, D.L. Bijl, H.S. de Boer, V. Daioglou, J.C. Doelman, O.Y. Edelenbosch, M. Harmsen, A.F. Hof, and M.A.E. van Sluisveld, 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8** (5), 391–397. https://doi.org/10.1038/s41558-018-0119-8

191. National Academies of Sciences, Engineering, and Medicine, 2019: *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. The National Academies Press, Washington, DC, 510 pp. https://doi.org/10.17226/25259

192. Wang, C., Z.-H. Wang, and J. Yang, 2018: Cooling effect of urban trees on the built environment of contiguous United States. *Earth's Future*, **6** (8), 1066–1081. https://doi.org/10.1029/2018ef000891

193. Kovacs, K.F., R.G. Haight, S. Jung, D.H. Locke, and J. O'Neil-Dunne, 2013: The marginal cost of carbon abatement from planting street trees in New York City. *Ecological Economics*, **95**, 1–10. https://doi.org/10.1016/j.ecolecon.2013.08.012

194. Brown, M.E., J.M. Antle, P. Backlund, E.R. Carr, W.E. Easterling, M.K. Walsh, C. Ammann, W. Attavanich, C.B. Barrett, M.F. Bellemare, V. Dancheck, C. Funk, K. Grace, J.S.I. Ingram, H. Jiang, H. Maletta, T. Mata, A. Murray, M. Ngugi, D. Ojima, B. O'Neill, and C. Tebaldi, 2015: Climate Change, Global Food Security, and the U.S. Food System. U.S. Department of Agriculture, 146 pp. https://doi.org/10.7930/j0862dc7

195. García-Peña, G.E., A.V. Rubio, H. Mendoza, M. Fernández, M.T. Milholland, A.A. Aguirre, G. Suzán, and C. Zambrana-Torrelio, 2021: Land-use change and rodent-borne diseases: Hazards on the shared socioeconomic pathways. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **376** (1837), 20200362. https://doi.org/10.1098/rstb.2020.0362

196. Plowright, R.K., J.K. Reaser, H. Locke, S.J. Woodley, J.A. Patz, D.J. Becker, G. Oppler, P.J. Hudson, and G.M. Tabor, 2021: Land use-induced spillover: A call to action to safeguard environmental, animal, and human health. *The Lancet Planetary Health*, **5** (4), e237–e245. https://doi.org/10.1016/s2542-5196(21)00031-0

197. Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372** (6549), 8054. https://doi.org/10.1126/science.abc8054

198. Hausfather, Z. and G.P. Peters, 2020: Emissions—The 'business as usual' story is misleading. *Nature*, **577** (7792), 618–620. https://doi.org/10.1038/d41586-020-00177-3

199. O'Neill, B.C., C. Tebaldi, D.P. van Vuuren, V. Eyring, P. Friedlingstein, G. Hurtt, R. Knutti, E. Kriegler, J.F. Lamarque, J. Lowe, G.A. Meehl, R. Moss, K. Riahi, and B.M. Sanderson, 2016: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, **9** (9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

200. Wickham, J., S.V. Stehman, D.G. Sorenson, L. Gass, and J.A. Dewitz, 2021: Thematic accuracy assessment of the NLCD 2016 land cover for the conterminous United States. *Remote Sensing of Environment*, **257**, 112357. https://doi.org/10.1016/j.rse.2021.112357

201. Wang, M., M. Wander, S. Mueller, N. Martin, and J.B. Dunn, 2022: Evaluation of survey and remote sensing data products used to estimate land use change in the United States: Evolving issues and emerging opportunities. *Environmental Science & Policy*, **129**, 68–78. https://doi.org/10.1016/j.envsci.2021.12.021

202. Friedlingstein, P., M.W. Jones, M. O'Sullivan, R.M. Andrew, D.C.E. Bakker, J. Hauck, C. Le Quéré, G.P. Peters, W. Peters, J. Pongratz, S. Sitch, J.G. Canadell, P. Ciais, R.B. Jackson, S.R. Alin, P. Anthoni, N.R. Bates, M. Becker, N. Bellouin, L. Bopp, T.T.T. Chau, F. Chevallier, L.P. Chini, M. Cronin, K.I. Currie, B. Decharme, L.M. Djeutchouang, X. Dou, W. Evans, R.A. Feely, L. Feng, T. Gasser, D. Gilfillan, T. Gkritzalis, G. Grassi, L. Gregor, N. Gruber, Ö. Gürses, I. Harris, R.A. Houghton, G.C. Hurtt, Y. Iida, T. Ilyina, I.T. Luijkx, A. Jain, S.D. Jones, E. Kato, D. Kennedy, K. Klein Goldewijk, J. Knauer, J.I. Korsbakken, A. Körtzinger, P. Landschützer, S.K. Lauvset, N. Lefèvre, S. Lienert, J. Liu, G. Marland, P.C. McGuire, J.R. Melton, D.R. Munro, J.E.M.S. Nabel, S.I. Nakaoka, Y. Niwa, T. Ono, D. Pierrot, B. Poulter, G. Rehder, L. Resplandy, E. Robertson, C. Rödenbeck, T.M. Rosan, J. Schwinger, C. Schwingshackl, R. Séférian, A.J. Sutton, C. Sweeney, T. Tanhua, P.P. Tans, H. Tian, B. Tilbrook, F. Tubiello, G.R. van der Werf, N. Vuichard, C. Wada, R. Wanninkhof, A.J. Watson, D. Willis, A.J. Wiltshire, W. Yuan, C. Yue, X. Yue, S. Zaehle, and J. Zeng, 2022: Global carbon budget 2021. *Earth System Science Data*, **14** (4), 1917–2005. https://doi.org/10.5194/essd-14-1917-2022

203. O'Neill, B.C., T.R. Carter, K. Ebi, P.A. Harrison, E. Kemp-Benedict, K. Kok, E. Kriegler, B.L. Preston, K. Riahi, J. Sillmann, B.J. van Ruijven, D. van Vuuren, D. Carlisle, C. Conde, J. Fuglestvedt, C. Green, T. Hasegawa, J. Leininger, S. Monteith, and R. Pichs-Madruga, 2020: Achievements and needs for the climate change scenario framework. *Nature Climate Change*, **10** (12), 1074–1084. https://doi.org/10.1038/s41558-020-00952-0

204. USDA Interagency Agricultural Projections Committee, 2023: USDA Agricultural Projections to 2032. Long-Term Projections Report OCE-2023-1. U.S. Department of Agriculture, World Agricultural Outlook Board, Office of the Chief Economist, 119 pp. https://www.usda.gov/sites/default/files/documents/USDA-Agricultural-Projections-to-2032.pdf

205. Calvin, K., B. Bond-Lamberty, A. Jones, X. Shi, A. Di Vittorio, and P. Thornton, 2019: Characteristics of human-climate feedbacks differ at different radiative forcing levels. *Global and Planetary Change*, **180**, 126–135. https://doi.org/10.1016/j.gloplacha.2019.06.003

206. Kline, K.L., N. Singh, and V.H. Dale, 2013: Cultivated hay and fallow/idle cropland confound analysis of grassland conversion in the Western Corn Belt. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (31), E2863–E2863. https://doi.org/10.1073/pnas.1306646110

207. Anderson, K. and G. Peters, 2016: The trouble with negative emissions. *Science*, **354** (6309), 182–183. https://doi.org/10.1126/science.aah4567

208. Calvin, K., A. Cowie, G. Berndes, A. Arneth, F. Cherubini, J. Portugal-Pereira, G. Grassi, J. House, F.X. Johnson, A. Popp, M. Rounsevell, R. Slade, and P. Smith, 2021: Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy*, **13** (9), 1346–1371. https://doi.org/10.1111/gcbb.12863

209. Krause, A., T.A.M. Pugh, A.D. Bayer, W. Li, F. Leung, A. Bondeau, J.C. Doelman, F. Humpenöder, P. Anthoni, B.L. Bodirsky, P. Ciais, C. Müller, G. Murray-Tortarolo, S. Olin, A. Popp, S. Sitch, E. Stehfest, and A. Arneth, 2018: Large uncertainty in carbon uptake potential of land-based climate-change mitigation efforts. *Global Change Biology*, **24** (7), 3025–3038. https://doi.org/10.1111/gcb.14144

Fifth National Climate Assessment: Chapter 7

# Forests

# Chapter 7. Forests

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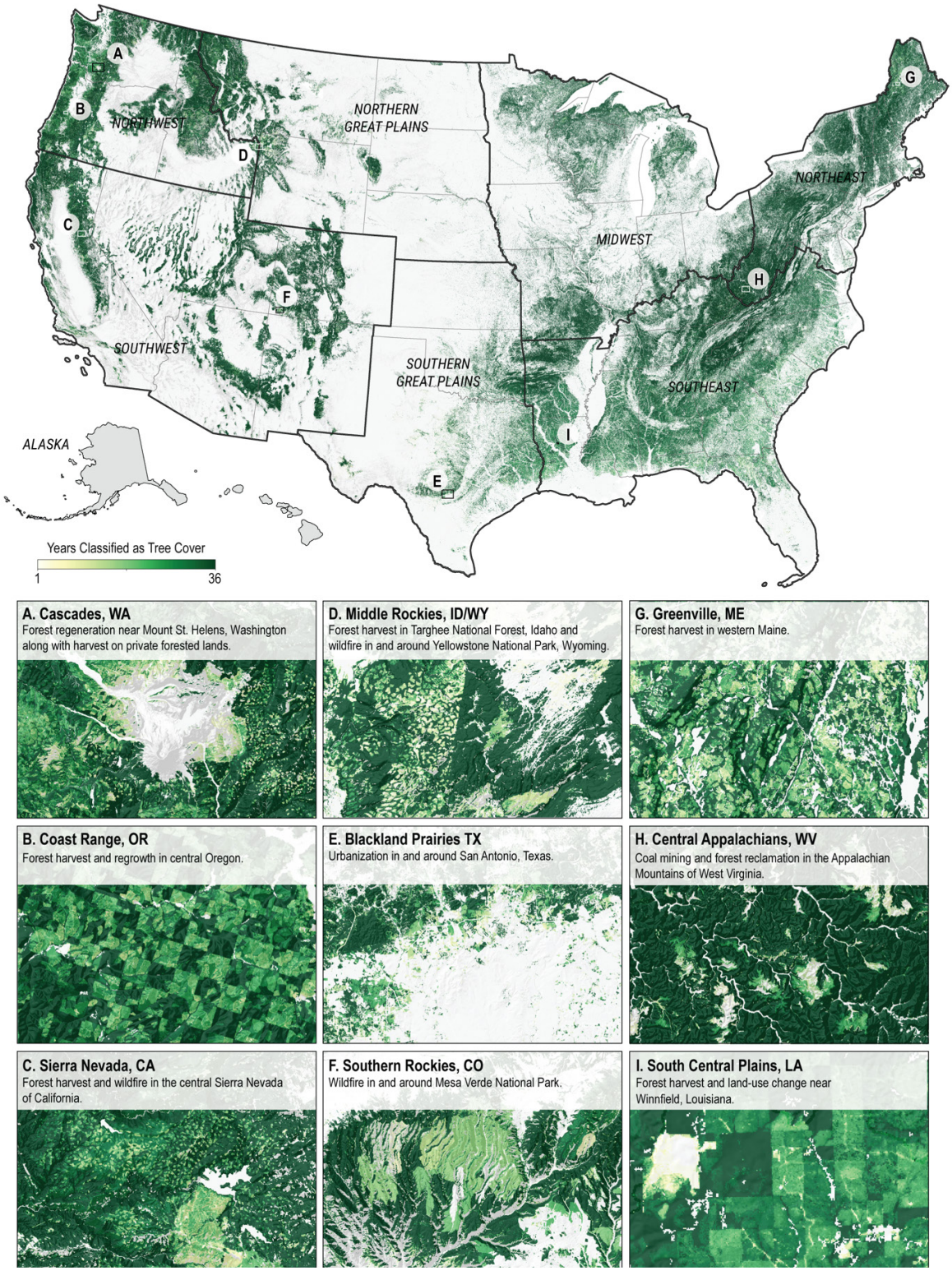
# Introduction

Forest ecosystems provide ecological, economic, and social goods and services (hereafter ecosystem services) to natural systems and humankind. These include air purification; regulating water quantity and quality; provisioning fish and wildlife habitat, food, medicine, shelter, wood, and other forest products; provisioning aesthetics, outdoor recreation, and spiritual renewal; and regulating climate through carbon transfers and other processes.[1] The livelihoods, health, nutrition, and cultural practices and traditions of many Indigenous and Tribal Peoples depend on forest ecosystems (Ch. 16). Social and economic drivers influence how and when forests are managed to maintain or restore ecosystem services critical to human health and welfare.

Forests represent more than one-third (766 million acres) of the land base in the US, with an additional 125 million acres of trees outside of forests in woodlands and developed areas. The amount of forest and tree cover has remained relatively stable over the last 100 years despite substantial land-use change into and out of forest and tree cover, especially in recent decades (Figures 7.1, 6.2).[2] Forest land area and tree cover have declined slightly in the contiguous US in the last two decades due mostly to cropland expansion and urbanization (Figure 6.4),[3,4] including expansion of the wildland–urban interface (WUI).[5] Forests contributed more than 4% of total US manufacturing gross domestic product in 2020 (nearly $336 billion in 2022 dollars), and the forest products industry is among the top 10 manufacturing sector employers in the US.[6]

## Tree Cover Dynamics

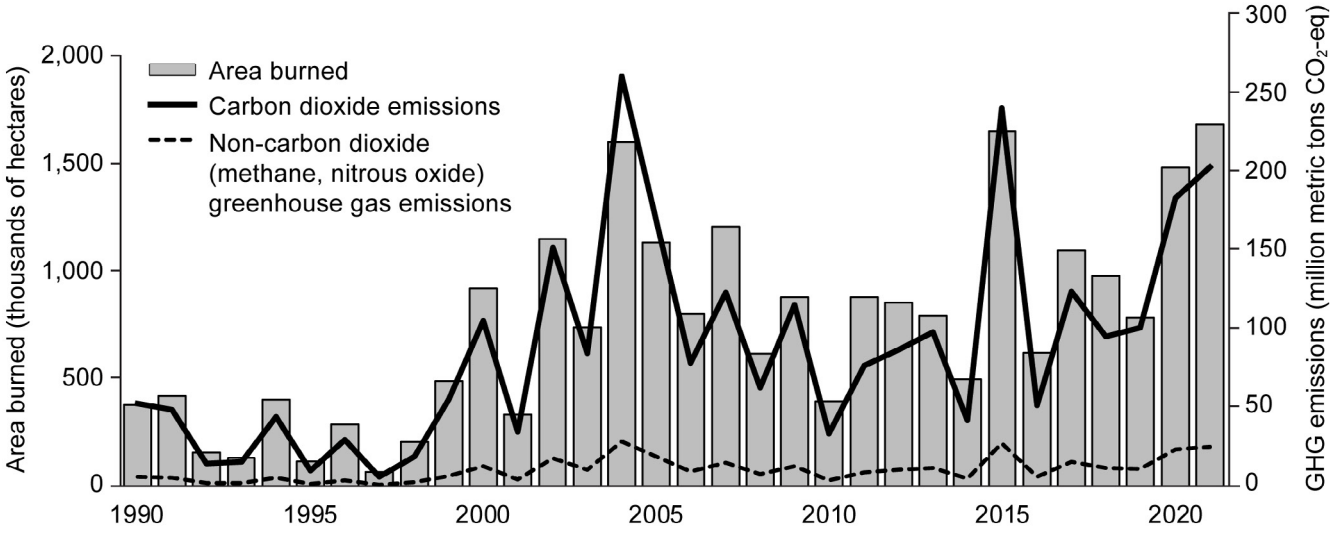



**The persistence of tree cover in the United States varies due to many driving forces.**

**Figure 7.1.** This figure shows the number of years each 30 m by 30 m pixel was classified as forest cover during 1985–2020. Insets (**A–I**) show that patterns of forest cover vary considerably across regions, often due to differences in the factors causing forest change. Patterns in tree cover change in the US are driven, in large part, by climate-related disturbances, land use, and land-use change. Data were unavailable for Alaska, Hawai'i and the Affiliated US Pacific Islands, and the US Caribbean. Figure credit: USGS.

The vulnerability of US forests to climate change and climate-related disturbances varies (relative to natural variability) due to differences in biophysical conditions and local and regional variations in climate (Chs. 2, 3). For example, although 21st-century temperatures (2001–2020) have increased almost everywhere in the US (relative to 1951–1970), this warming has not occurred uniformly across the US (KM 3.4; Figure 3.11). Due to these differences, the capacity of some US forests to provide ecosystem services is increasingly affected by climate change and climate-related disturbances (KMs 7.1, 7.2).[7] For example, the amount of forest burned and greenhouse gas (GHG) emissions from fires have increased substantially since 1990, mostly in the West, with three of the five worst wildfire years (based on area burned and GHG emissions) occurring since 2015 (Figure 7.2).[3] Proactive adaptation will assist the provisioning of ecosystem services from forests. Examples of adaptation in US forests have proliferated since 2017 (KM 7.3; Ch. 31) on federal, state, local, Tribal, and private lands (e.g., Moser et al. 2019;[8] USDA 2022,[9] 2021[10]). The effects of climate change on forests in specific regions of the US are discussed in several of the regional chapters (e.g., Chs. 21–24, 27–29).

## Estimated Annual Greenhouse Gas (GHG) Emissions from Wildfires and Prescribed Fires




**The amount of forest area burned and associated greenhouse gas emissions have increased in recent decades in the United States.**

**Figure 7.2.** Estimated forest area burned and greenhouse gas emissions (carbon dioxide, methane, and nitrous oxide) from wildfires and prescribed fires in the contiguous US and Alaska have increased since the late 1990s. Climate change is affecting the likelihood and scale of wildfires in US forests. In some cases, wildfires (particularly in the western US) have slowed or stopped recovery of forests from previous disturbances, reducing their capacity to sequester and store carbon. Adapted from Domke et al. 2023.[3]

## Key Message 7.1

## Forests Are Increasingly Affected by Climate Change and Disturbances

Climate change is increasing the frequency, scale, and severity of some disturbances that drive forest change and affect ecosystem services (*high confidence*). Continued warming and regional changes in precipitation are expected to amplify interactions among disturbance agents (*likely*, *high confidence*) and further alter forest ecosystem structure and function (*likely*, *high confidence*).

Climate change affects disturbances such as wildfires, insects, diseases, and land uses, as well as the interactions among these disturbances, all of which shape forest ecosystems through changes in growth, mortality, regeneration, and recruitment of vegetation over space and time (Figure 6.1 in Vose et al. 2018[11]). Disturbances altered by climate change pose risks to current and future forest health (i.e., the extent to which ecosystem processes are functioning within their natural range of historical variation) and will affect forest conditions across landscapes for years to centuries. Weather events such as droughts, hurricanes, windstorms, and floods may exacerbate disturbance effects, especially in extreme cases (Figure 7.3; Chs. 8, 9). The exposure and sensitivity of forests to climate change and climate-related disturbances vary with disturbance, forest condition, management history, and the rate and magnitude of change.

### Coastal Ghost Forest

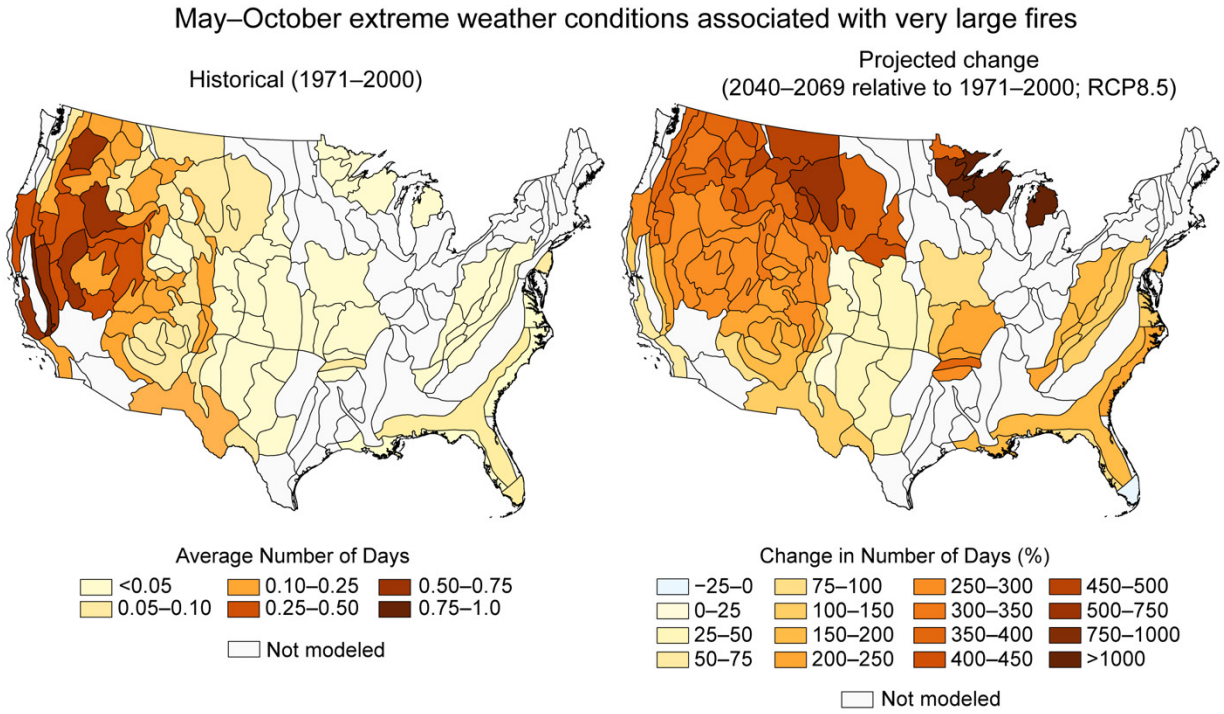
**Coastal ghost forests result when trees are killed by sea level rise and saltwater intrusion.**

**Figure 7.3.** The photo shows a coastal ghost forest (foreground) near Blackwater National Wildlife Refuge, Maryland. As sea levels rise in response to climate change, the replacement of coastal forests with tidal wetlands will affect many ecosystem services, including storm surge buffering capacity. Photo credit: ©Matthew L. Kirwan, Virginia Institute of Marine Science.

Climate change is affecting the likelihood and scale of wildfires in US forests. For example, the amount of forest burned by wildfires in the West has increased relative to the mid- to late 20th century[12,13] due, in part, to warming increasing vapor pressure deficits and rates of evapotranspiration (KM 4.1),[12,14] as well as decreases in precipitation (KM 4.1).[15] Fire activity is projected to increase with further warming and reductions in precipitation,[14,16] although increases depend on regional fuel types and may eventually decrease in some forests due to reductions in fuel loads.[17] The area burned by high-severity wildfires (e.g., stand-replacing fires) has increased in the West since 1985 by about eightfold,[18] partly due to warmer, drier conditions (Figure 7.4; KM 2.1). Where abundant fuels are available, western US forests have experienced an increase in the proportion of area burned at high severity, especially in the Southwest (KM 28.5).[18] Increased fire severity is expected to become more widespread in US forests in the future.[19] Atypical re-burns and levels of fuel flammability that were historically rare are expected to become more common (Focus on Western Wildfires).

Determining the effects of climate change on wildfires is more difficult in regions outside the West, for example, in areas where prescribed fire use has changed substantially over time (Southeast), where wildfire was historically rare (Northeast), and where forests represent a small portion of the landscape (agricultural regions in the central US). Furthermore, fire intensity (energy released during wildfire) and severity depend on fuel availability and flammability, which are directly affected by management (including wildfire suppression) and land use,[20] as well as climate-driven changes in weather. However, altered meteorological conditions (e.g., relative humidity and wind speed), especially extreme conditions promoting wildfire spread, have become more prevalent in recent decades[21] and are attributed, in part, to climate change (KM 2.2).[22] Changes in human demography in the WUI and increases in the ratio of human to natural fire ignitions[23] have combined with climate change to alter historical expectations of fire initiation and spread. One study found that a long-term trend in nighttime vapor pressure deficit, not simulated in climate models, explained recent fire managers' observations that the rates of spread of fires in the West slowed less at night.[24]

## Very Large Fires




**Conditions conducive to very large fires are projected to increase.**

**Figure 7.4**. The left panel shows historical (1971–2000) values for the annual number of days in May through October with extreme weather conditions conducive to very large fires (VLFs; more than 12,000 acres). The right panel shows the percent change in the number of days for a projected future (2040–2069) climate under a very high scenario (RCP8.5). Changes are summarized by Bailey ecosections, which are areas of similar vegetation and climate defined by Bailey (2016).[25] The number of days with conditions associated with VLFs more than doubles in many ecosections, with more than a fourfold increase for parts of the Northwest, fivefold for the northern Rockies, and over sevenfold for the Upper Midwest. Projected conditions are an average of a 17-GCM (global climate model) ensemble selected for data availability. Areas with no color indicate lack of data (sufficient data are unavailable or where wildfires were historically rare). Data were unavailable for Alaska, Hawai'i and the Affiliated US Pacific Islands, and the US Caribbean. Figure credit: USGS.

In addition to wildfire, native and invasive (non-native) insects, diseases, and plants are important forest disturbances with climatic and non-climatic factors influencing their extent and effects. Tree mortality from bark beetles in the West has increased in the late 20th and early 21st centuries due, in part, to climate change (Box 7.1).[26,27,28,29] The effects of climate change on other forest insects and diseases are less certain. For example, white pine blister rust (a disease caused by the non-native fungus *Cronartium ribicola*) is expected to decrease where conditions become warmer and drier (Southwest) but increase where conditions become warmer and wetter (high-elevation subalpine forests).[30] Warming, altered precipitation patterns, extreme events, and disturbances all influence invasion pathways and may facilitate the establishment and spread of invasive species (KM 8.2).[31] In Hawai'i, climate change and the spread of invasive grasses have increased the frequency and extent of wildfires.[32] In the Southeast, warming temperatures have allowed cold-sensitive invasive species like kudzu to move farther north,[33] affecting forest structure and composition. Kudzu and other woody vines are stimulated by increased carbon dioxide ($CO_2$)[34] and in some cases outcompete trees and other plants.[35] Even in the absence of other disturbances, warming and drought are important drivers of tree mortality in the US and globally.[36]

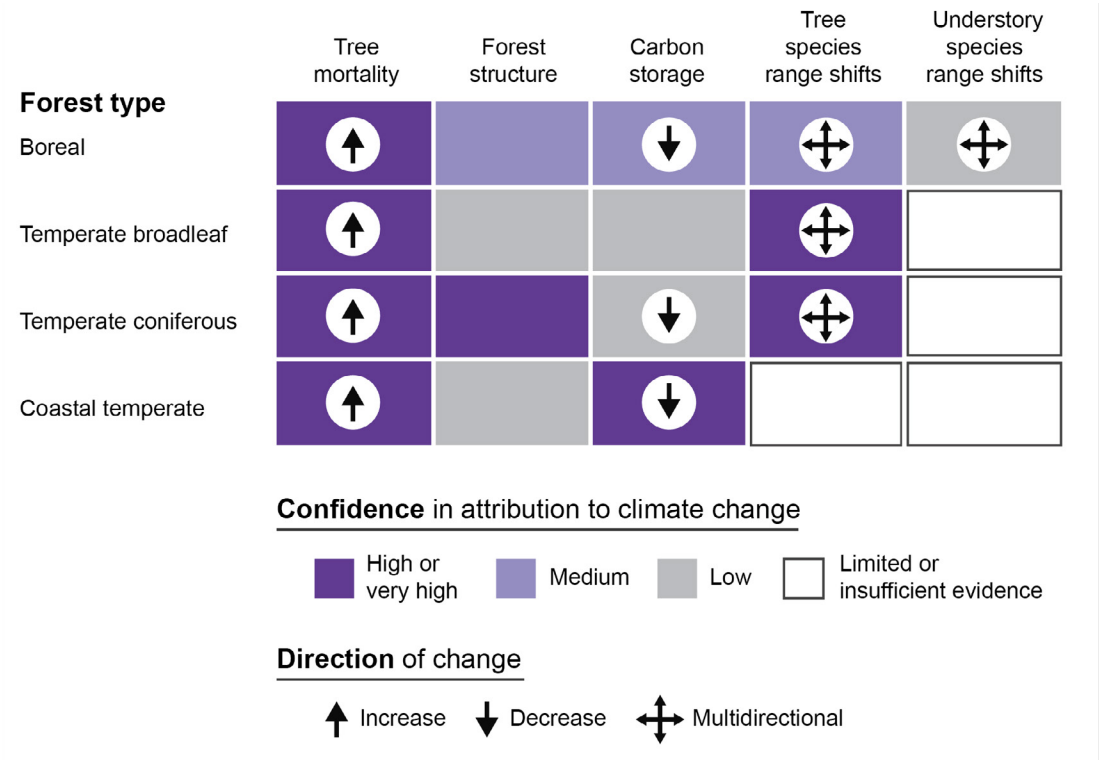
Sea level rise, another climate-related disturbance, affects the distribution, structure, and composition of forests (KM 9.2). Saltwater intrusion has reduced the health, diversity, and productivity of some coastal

forests in the East (Figure 7.3).[37] Sea level is projected to result in the loss of existing mangrove forests in many places in future decades.[38,39,40] However, warming during winter has facilitated northward migration of mangroves in the Southeast (Figure 7.7).[41]

Forest structure, function, and diversity are affected across a broad range of spatial scales (Figure 7.5). Variation in environmental conditions, historical and contemporary disturbances, management history, and land use have modified many forests, making them more vulnerable to droughts, wildfires, and other disturbances.[42] These disturbances accelerate tree mortality; alter tree and other plant species distributions, age and size distributions, and regeneration success; and can lead to conversion to non-forest ecosystems (e.g., Falk et al. 2022;[43] Stanke et al. 2021[44]).

Ecological transformations and shifts in forest habitats are occurring because of climate change (KM 8.1).[45] In some low-elevation forests in the West, tree regeneration over the last 20 years has been limited by unfavorable climate. High wildfire severity and low seed availability has further reduced postfire regeneration in some locations.[46,47] Eastern tree species migration is associated with increased seed production but is limited to some extent by the occurrence and distribution of large urban areas in the East.

## Effects of Climate Change on Forests




**Climate change and climate-related disturbances are affecting forests in the United States.**

**Figure 7.5.** The figure shows recently documented effects, specific to individual forest types, that have been attributed to climate change and climate-related disturbances. Effects include increased tree mortality across all types with high confidence, changes in forest structure with variable confidence, less carbon storage across three of the four forest types, and variable shifts in plant species composition. Confidence levels reflect the uncertainty in attributions based on available literature. Arrows indicate the direction of change where suitable data exist. In the case of temperate forests, structure is changing but not in a unidirectional way. Boreal forest reflects changes only in Alaska. Assessments in the figure are based on recent relevant literature, and citations can be found in the metadata. Adapted with permission from Figure SPM.2 in IPCC 2022.[48]

Although the effects of climate change on tree species have been well studied, effects on understory plants are poorly understood.[49] In Wisconsin, shifts in understory plant species lag regional climate changes, but less so for species with broader site occupancies and larger seed masses.[50] In Oregon's Siskiyou Mountains, average temperature increases of about 3.6°F since 1948 have caused differing effects on plant communities. Low-elevation herb communities are now consistent with a hotter, drier climate and resemble plant communities in more southerly topographic positions. At higher elevations, herbs of northern biogeographic affinity have increased.[51]

Some management activities and land-use changes, especially rapid expansion of the WUI,[5] have reduced the adaptive capacity of forests to variations in climate and climate-related disturbances.[52,53,54] The WUI is more prevalent in the East but is expanding at a faster rate in the West.[5] In the East, forests in the WUI retain larger trees and aboveground biomass than less developed forests, but with less structural diversity (i.e., WUI forests have fewer saplings, seedlings, and dead trees). This raises concerns about diminished ecological function, reduced diversity of wildlife habitat, and vulnerability to warming.[55] In the West, wildfire exclusion in dry forests historically adapted to frequent wildfire has altered forest structure and composition, resulting in higher surface and canopy fuel loads and increased vulnerability to high-severity wildfire.[56,57]

## Box 7.1. Bark Beetles and Climate Change

Bark beetles spend most of their lives within a host tree, feeding and reproducing beneath the bark. Climate change has increased the impacts of some bark beetles due to 1) warming, which in some cases has increased life cycles and decreased overwintering mortality of beetles within the host tree; and 2) drought, as drought-stressed hosts have compromised defenses and offer little resistance to colonization by bark beetles.[26,27,58] Warming during summer increases the probability of a spruce beetle completing its life cycle in one year compared to two years,[59] which has increased spruce beetle populations in some areas (Figure 7.6). In California, warming and drought incited mortality of more than 100 million trees during 2014–2017, most attributed to western pine beetles (Figure 7.6) colonizing ponderosa pines.[60,61] About 30% of the tree mortality in California was attributed to warming accelerating the life cycle of western pine beetle, with the remainder attributed to increases in host susceptibility due to drought stress.[29] The biomass of ponderosa pines in California may not return to levels that occurred prior to the drought due to future warming, droughts, and western pine beetle outbreaks.[62]

Warming has allowed mountain pine beetles to erupt at elevations and latitudes where winters historically were cold enough to kill most mountain pine beetle brood within the host tree.[26] In New York and New England, a recent climate-driven range expansion of southern pine beetle resulted in a new bark beetle-host interaction in pitch pine forests.[63] In Alaska, an ongoing spruce beetle outbreak has affected more than 1.6 million acres since 2016 and expanded into the Alaska Range,[27] threatening spruce forests in interior Alaska, where spruce beetle populations were historically regulated by cold winter temperatures.[64]

Bark beetle outbreaks are often detrimental to the provision of ecosystem services,[65] and can affect other disturbances and their effects on ecosystem services. For example, in some forests, mountain pine beetle outbreaks have increased the severity of wildfires[66] and the abundance of invasive weeds.[67] Silvicultural interventions such as thinning to reduce tree densities can be used to increase the resistance and resilience of some forests to bark beetles (KM 7.3), a relationship attributed to decreases in tree competition and associated increases in tree vigor, among other factors.[27]

### Spruce and Pine Beetle Outbreaks

**Outbreaks of spruce and pine beetles, partly attributable to climate change, are killing trees in the West.**

**Figure 7.6.** These photos show a spruce beetle outbreak on the Bridger–Teton National Forest in Wyoming (**left**) and a western pine beetle outbreak on the Sierra National Forest in California (**right**). Discolored trees were colonized and killed by bark beetles. Warming and drought have increased the impacts of some bark beetles in US forests, affecting many ecosystem services. Photo credits: Christopher J. Fettig, USDA Forest Service.

## Key Message 7.2

## Climate Change Affects Ecosystem Services Provided by Forests

Climate change threatens the ecosystem services forests provide that enrich human lives and sustain life more broadly. Increasing temperatures, changing precipitation patterns, and altered disturbances are affecting the capacity of forest ecosystems to sequester and store carbon (*high confidence*), provide clean water and clean air (*high confidence*), produce timber and non-timber products (*high confidence*), and provide recreation (*medium confidence*), among other benefits. Future climate effects will interact with societal changes to determine the capacity of forests to provide ecosystem services (*likely, high confidence*).

Some effects of climate change and climate-related disturbances on ecosystem services and their associated economic benefits are gradual, driven by annual or seasonal warming, altered precipitation patterns, or sea level rise. Others are more rapid, driven by extreme events such as droughts, hurricanes, or heatwaves. Co-occurrence and/or interactions among disturbances (compound disturbances) can amplify the effects of individual disturbances on ecosystem services (Box 7.1; Figure 7.7; KM 2.3).[68,69]

Climate change is projected to affect forest growth domestically and internationally, wood and paper markets (e.g., Tian et al. 2016[70]), and the amount of carbon stored in harvested wood products (Box 7.2; KM 12.2; e.g., Johnston and Radeloff 2019[71]). However, the strength of these effects is uncertain due to disturbances, such as droughts, wildfires, insects, and diseases, that limit forest growth.[72] Forest management actions taken in response to climate change can also affect timber product outputs, carbon, and associated ecosystem services (e.g., Creutzburg et al. 2017[73]). Sea level rise also directly and indirectly affects timber output and carbon storage through loss of coastal forests to saltwater intrusion and housing losses and rebuilding, with a projected 800,000 new residential units needed in the US by 2050 to accommodate relocations due to sea level rise under a very high scenario (RCP8.5).[74]

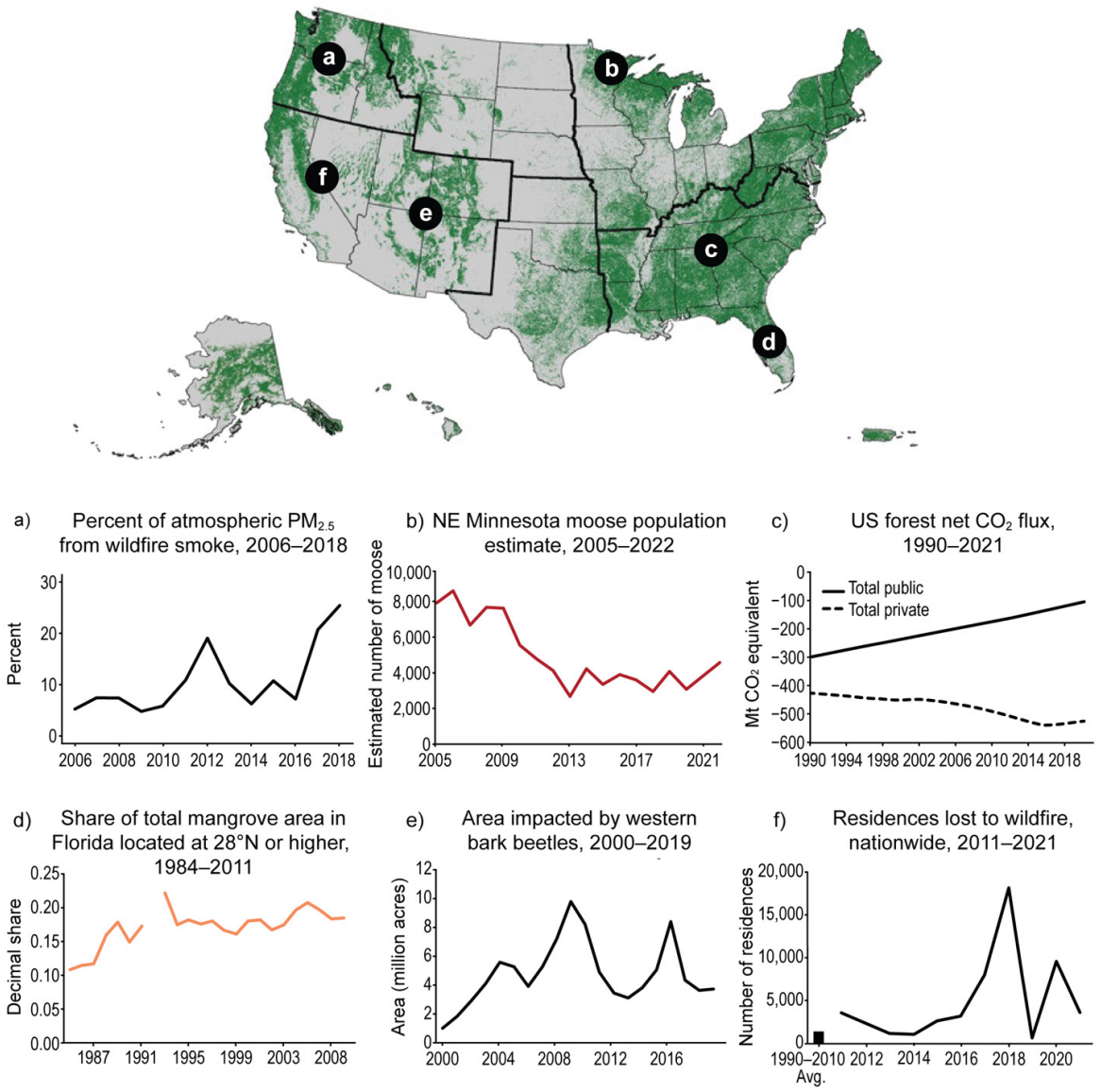
Climate change is altering the ranges and abundances of some plants and fungi used for food, medicine, and other purposes. Reduced snow depth, for example, can increase plant injury and mortality through increased exposure of tissues to frosts,[75,76,77] as well as reduced microbial biomass and activity.[78,79] Many plants and fungi have precise ecological requirements and narrow geographic ranges, leaving them vulnerable to climate change.[80] Some species are at their range limits, unable to adapt to rapidly changing conditions.[81] Effects differ by plant and fungal species, relating to their sensitivity and adaptive capacity.

Climate change affects heritage values, cultural identity, and spiritual connections associated with forests, exacerbating environmental injustices affecting Indigenous and Tribal food sovereignty, health, cultural practices, and knowledge transmission (Chs. 16, 20).[82] Examples of culturally significant species affected by climate change include salmon, brook trout, oaks, pinyon pine, and whitebark pine (Box 7.3).[83,84,85,86,87] In 2023, whitebark pine was listed as a threatened species by the US Fish and Wildlife Service, with white pine blister rust, mountain pine beetle, altered wildfire patterns, and climate change identified as major threats to its existence.[88] Climate-related changes highlight fluctuating consistency, timing, and availability of culturally significant foods, fibers, and medicines.[89,90,91]

Climate change decreases some forest-based recreational activities and increases others. For example, warming and reduced snowpack have had negative effects on winter sports (e.g., cross-country skiing, snowshoeing, and snowmobiling) and positive effects on warm-weather activities, with mixed effects on water-based activities.[92] Participation in fishing and motorized water activities is projected to increase in the North, while motorized water activities are projected to decrease in parts of the West.[93]

Increases in the amount of forest burned by wildfires are creating negative human health effects and growing economic losses.[94] Increases in wildfire smoke are increasing respiratory and cardiovascular-associated hospitalizations (KM 14.2; Focus on Western Wildfires)[95] and out-of-hospital cases of cardiac arrest.[96] Chemicals mobilized into the environment from wildfire-ignited structures and infrastructure can differ from those emitted from burning forest fuels, potentially increasing human health concerns (KM 14.2).[97,98]

## Forest Ecosystem Services




**Climate change has affected the provisioning of forest ecosystem goods and services in the United States.**

**Figure 7.7.** (**a**) Increases in fine particulate matter air pollutants ($PM_{2.5}$) caused by wildfires degrade air quality and increase human health risks (data for Alaska, Hawai'i, Puerto Rico, US Virgin Islands, and US-Affiliated Pacific Islands are not available). (**b**) Reduction in moose hunting opportunities stems from climate-related increases in parasites; declines in hunting opportunities have also been noted in the western US.[99] (**c**) Increased tree mortality is shrinking carbon sequestration in public forests (Mt is millions of metric tons). (**d**) Northward migration of mangroves is displacing saltwater marshes, altering coastal storm protection and affecting recreation (data for 1992 are not available). (**e**) Increased tree mortality by western bark beetles lowers home values through reduced environmental amenities.[100] (**f**) Housing losses due to wildfires increased by fivefold in the 2010s compared to the average from 1990 to 2010, with substantial interannual variability; data exclude losses from US-Affiliated Pacific

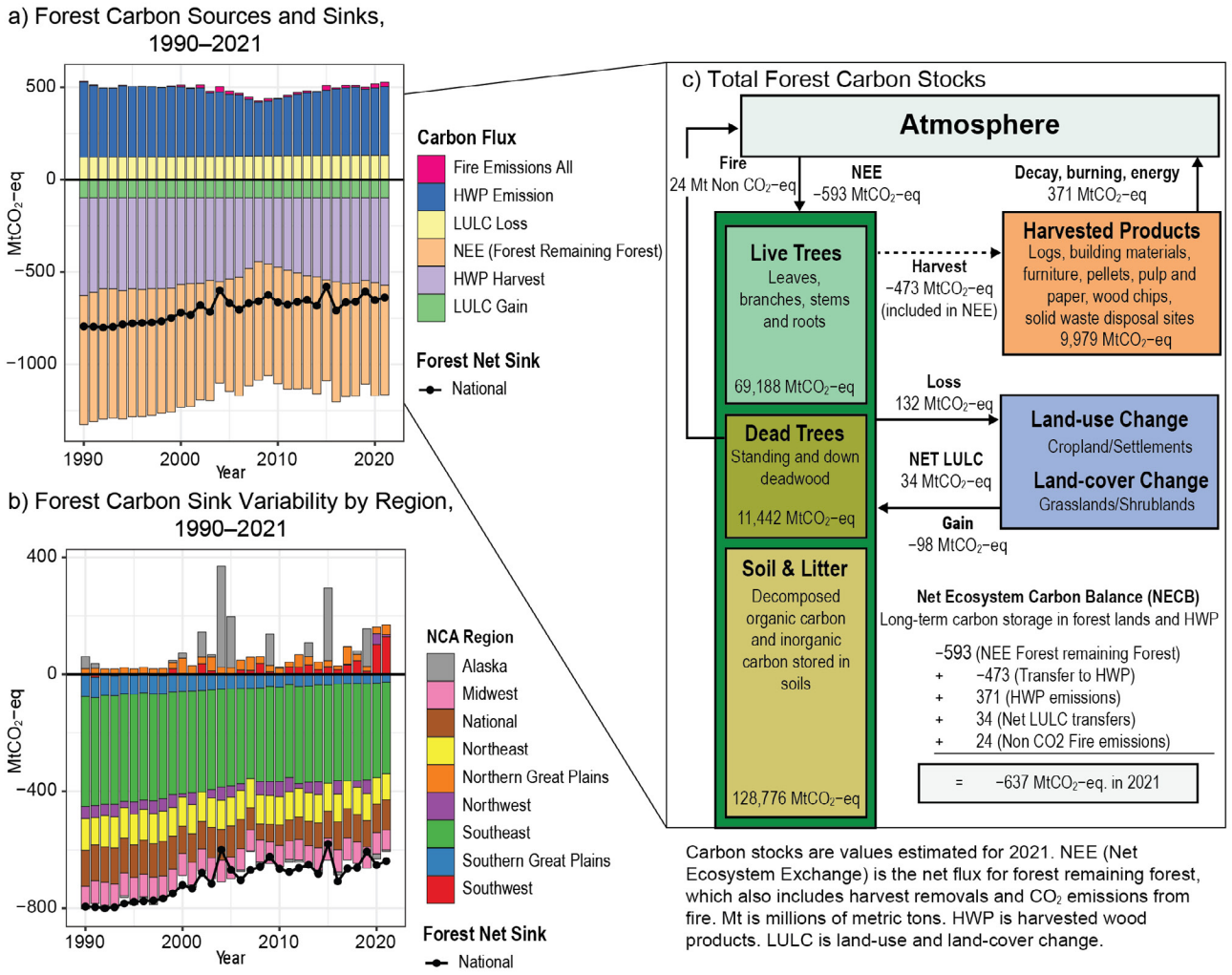
Islands. Notes: Map excludes depictions of forest area for the US Virgin Islands and US-Affiliated Pacific Islands due to the large scale of the map. US Virgin Islands forest area is 46,967 acres.[101] Forest areas for US-Affiliated Pacific Islands are as follows: Federated States of Micronesia (143,466 acres), Marshall Islands (23,252 acres), Northern Mariana Islands (75,407 acres), Palau (90,685 acres), American Sāmoa (43,631 acres), and Guam (63,833 acres); US Affiliated Pacific Island summary data are from sources cited in Lugo et al. 2022.[102] Figure credits: (top) USDA Forest Service; (a) adapted with permission from Burke et al. 2021;[103] (b) USDA Forest Service; (c) adapted from Domke et al. 2023;[3] (d) USDA Forest Service; (e) adapted from Fettig et al. 2022;[27] (f) USDA Forest Service.

Extreme events have been linked to declines in populations of amphibians, birds, fish, invertebrates, mammals, plants, and reptiles (KM 8.2).[104] Recent insect population declines have been attributed, in part, to climate change, with wide-reaching consequences.[105,106] Climate change is increasing the intensity of hurricanes in the East and their associated rainfall,[107,108] although projected changes in the frequency of hurricanes due to warming are uncertain (Chs. 2, 3; e.g., Sobel et al. 2021[109]). Increased intensities of hurricanes could affect the structure and function of forests and wildlife habitat (e.g., Brown et al. 2011[110]). Mobile species or species capable of rapid population growth (e.g., invasives) generally benefit from extreme events and abrupt disturbances.[104]

## Box 7.2. Forests and Carbon

Carbon is continuously cycled between the Earth and atmosphere. Forests help regulate climate, as live plants remove carbon dioxide ($CO_2$) from the atmosphere through photosynthesis, facilitating maintenance and growth, and release some of that carbon through respiration. Forest ecosystems are the largest terrestrial carbon sink on Earth.[111] In the US, the amount of carbon stored in forests (primarily in soils and trees), as well as in harvested wood products that are either in use (e.g., paper, plywood) or in solid waste disposal sites (e.g., landfills), is equivalent to nearly three decades of fossil fuel emissions. On average, between 2017 and 2021, forest ecosystem carbon uptake has offset the equivalent of more than 13% of economy-wide $CO_2$ emissions each year.[3] In recent decades, the rate of forest carbon sequestration has slowly declined, in part due to increasing frequency and severity of climate-related disturbances, leading to interannual variability in the forest carbon sink and abrupt (e.g., wildfire) and/or gradual (e.g., insect outbreak) transfers of carbon to the atmosphere, dead organic matter pools (dead wood, litter), and soils (Figure 7.8; KM 6.1).[112,113] In some cases, climate-related disturbances have slowed or stopped recovery of forests, reducing their capacity to store carbon (Figure 7.8b),[62,114,115,116] and these trends are projected to continue under multiple climate, land-use, and socioeconomic scenarios. Human activities such as forest management (e.g., timber harvesting, prescribed fire, and other silvicultural interventions) are also major drivers of forest ecosystem carbon dynamics. Harvesting, for example, results in the transfer of some carbon stored in live and dead trees to the atmosphere as well as to harvested wood products and may alter the capacity of forest ecosystems to store new carbon.[112,117] Land-use changes, including cropland expansion and urbanization, have also contributed to the decline in carbon sequestration and/or storage.[115,118] Yet managing forest ecosystems, including forest soils,[119] for the purposes of carbon sequestration and/or storage, along with many other ecosystem services, remains a relatively cost-effective strategy for mitigating climate change (KM 6.3; Ch. 32).[112,120,121,122]

## Forest Carbon Sink




**The forest carbon sink has declined in recent decades in the United States, with substantial interannual variability.**

**Figure 7.8.** The figure shows (**a**) the interannual variability in forest carbon sources and sinks during the period 1990–2021; (**b**) the interannual variability in the forest carbon sink in the US by National Climate Assessment region during 1990–2021; and (**c**) the total forest carbon stocks by ecosystem pool (boxes) and mean annual transfers among the atmosphere and forest ecosystem pools, harvested wood products, and land conversions (arrows) in 2021. Negative estimates indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere or transfer between ecosystem pools or land categories). Forest ecosystems are the largest carbon sink in the US. There is substantial interannual variability in greenhouse gas emissions and removals from forest land that is driven, in large part, by climate-related disturbances, land use, and land-use change. Figure credit: USDA Forest Service and USGS.

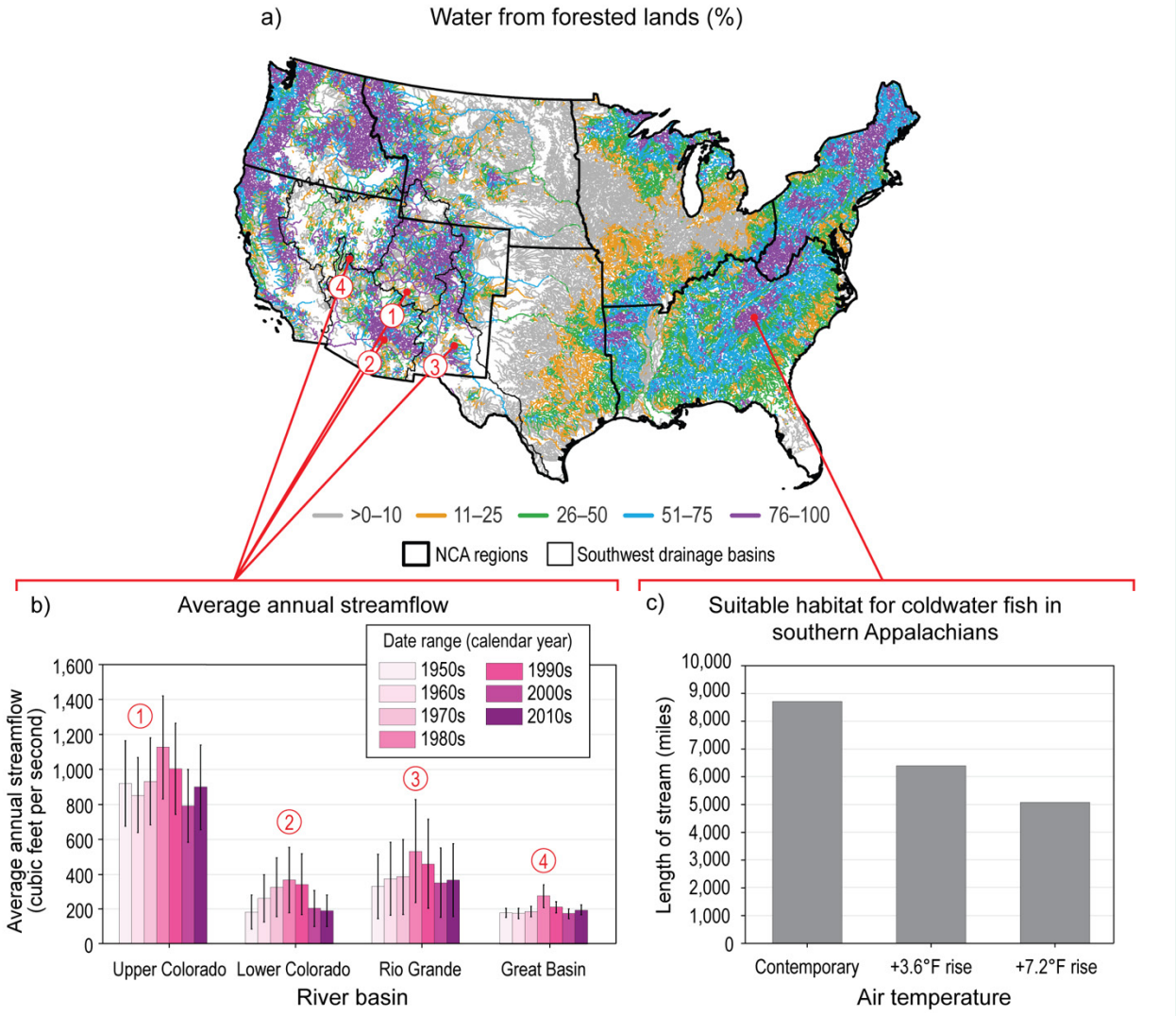
## Box 7.3. Climate Change Effects on Forest Water Resources

Forests are a critical source of water in the US (Figure 7.9a),[123,124] and climate change and climate-related disturbances are directly and indirectly affecting the availability and quality of water from forests. Warming across the West has resulted in reduced snowpack and earlier snowmelt and spring runoff, decreasing downstream water availability (KM 4.1).[125] In the Southwest, higher temperatures and reduced precipitation have decreased streamflow in recent decades (Figure 7.9b).[126] Shifts in precipitation and declining snowpacks are decreasing the magnitude and/or frequency of flooding in some areas but increasing them in others (Figure A4.8).[127,128] Models indicate that climate change will affect flood events as some watersheds transition from snow-dominated precipitation, or mixed rain and snow, to rain-dominated precipitation.[129,130] Wildfires and other disturbances (e.g., bark beetle outbreaks) can also result in changes in the availability and quality of water from forests.[131,132] Following wildfires, tree mortality decreases evapotranspiration, thereby increasing water runoff and supply.[133] However, wildfire also increases the runoff of sediments, metals, and other chemicals into water bodies for several years or more after a fire,[134] with higher rates of drinking-water standard violations occurring in burned versus unburned watersheds.[135]

Climate change impacts on water quantity and quality in turn affect aquatic life. Warming, drought, and declines in snowpack increase stream temperatures,[136] decreasing coldwater fish habitat (Figure 7.9c).[137,138,139] Shifts in precipitation from snow to rain are projected in much of southern Alaska.[140] Anticipated effects include changes in streamflow timing and magnitude, with negative effects on salmon production and salmon habitat.[141]

Adaptation measures can reduce some of the effects of climate change on water resources. Management practices, such as reintroducing American beaver, have increased water storage in some landscapes[142] but have had mixed effects on water quality for salmon in the Northwest.[143] Maximizing riparian forest buffers reduces erosion and sedimentation, provides habitat for wildlife, and is projected to delay or reduce stream warming through enhanced shading.[144] Thinning and surface-fuel reduction can lessen the risk of high-severity wildfires in fire-prone buffers and adjacent forests in the West,[145,146] with the potential to reduce fire severity and consequently the effects of wildfire on water resources.[132]

## Climate Effects on Forest Water Resources




**Climate change and climate-related disturbances are affecting the availability and quality of water from forests in the United States.**

**Figure 7.9.** Panel (**a**) shows the percent of surface water originating on forest lands across the contiguous US, illustrating that forests are a critical source of water. Panel (**b**) shows decadal average variations in average annual streamflow (measured in cubic feet per second [$ft^3/s$]) from Hydrologic Unit Code 8 (HUC8) watersheds with greater than 50% forest cover, no impoundments above the streamflow gauges, at least four gauges per basin, and complete records back to 1950 in the Great Basin (number of HUC8 gauges = 6), Upper Colorado (16), Lower Colorado (5), and Rio Grande (4). Data generally show annual streamflow has been comparatively lower in more recent years compared to earlier decades. Panel (**c**) shows projected changes in suitable coldwater fish habitat in the Southeast under 3.6°F and 7.2°F warming air temperature over contemporary (2012) air temperature. Projections suggest suitable coldwater fish habitat will decline in the future as air temperatures increase. Figure credits: (a) adapted from Liu et al. 2022;[124] (b, c) USDA Forest Service.

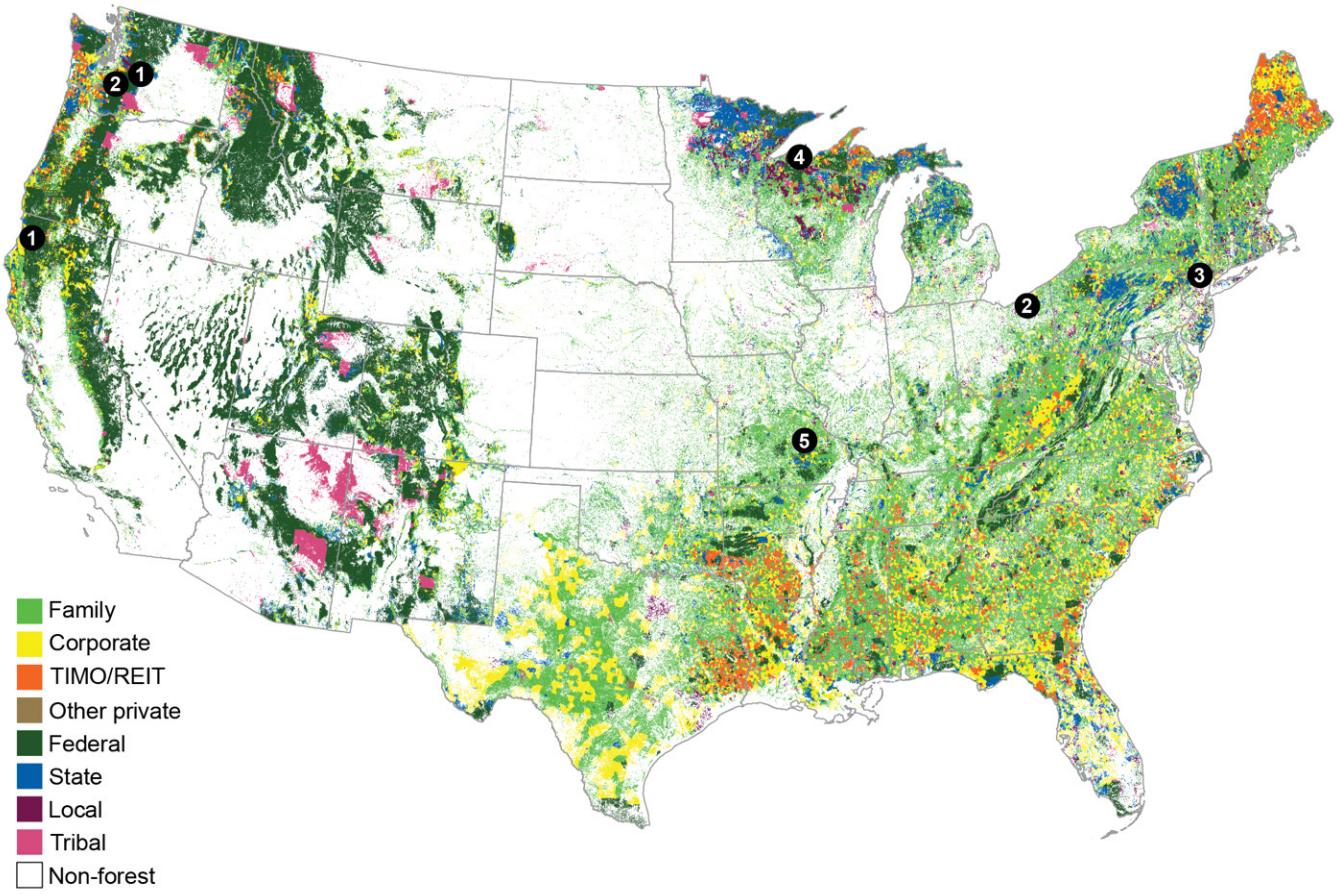
## Key Message 7.3

## Adaptation Actions Are Necessary for Maintaining Resilient Forest Ecosystems

Climate change creates challenges for natural resource managers charged with preserving the function, health, and productivity of forest ecosystems (*high confidence*). Forest landowners, managers, and policymakers working at local, state, Tribal, and federal levels are preparing for climate change through the development and implementation of vulnerability assessments and adaptation plans (*medium confidence*). Proactive adaptation of management strategies that create, maintain, and restore resilient forest ecosystems are critical to maintaining equitable provisioning of ecosystem services (*medium confidence*).

Proactive adaptation of forest management can help maintain the continued provisioning of ecosystem services from forests (e.g., Peterson and Halofsky 2018;[147] Voggesser et al. 2013[87]). Since 2017, the development of assessments, frameworks, and tools to guide adaptation in forests has accelerated. Climate change vulnerability assessments and adaptation plans for federal (e.g., Halofsky et al. 2016;[148] Timberlake and Schultz 2019[149]), state (Figure 31.1; e.g., Ontl et al. 2018;[150] PADEP 2021[151]), private,[152] and Tribal lands[91,153] have proliferated. Similarly, many guides and frameworks for adaptation have been introduced (e.g., Adaptation Partners 2023;[154] Schuurman et al. 2020[155]). Examples of implementation of adaptation practices in forests are now much more widespread (Figure 7.10; Table 7.1).

## Climate Adaptation and Forest Ownership




**Adaptation actions occur across many types of forest ownership and management in the United States.**

**Figure 7.10.** Forests in the eastern US are mostly privately owned, whereas the majority of forests in the western US are federally managed. Climate change adaptation actions have been implemented in diverse forest ownership settings. The numbers on the map correspond to locations of adaptation examples listed in Table 7.1 (example 6 is not depicted as it focuses on Puerto Rico, which is not shown on the map). TIMO = timber investment management organization; REIT = real estate investment trust. These data are not available for Alaska, Hawai'i, the US Caribbean, or the US-Affiliated Pacific Islands. Adapted from Sass et al. 2020.[156]

**Table 7.1. Examples of Climate Change Adaptation Actions in Forest Ecosystems**

| Map Location | Climate Change Effect | Adaptation Response | References and Resources |
|---|---|---|---|
| 1 | Longer wildfire season and increased area burned. | Thin forests and conduct prescribed and cultural burns to reduce the risk of high-severity wildfire and promote valued plants. | Long et al. 2021[157]<br>Marks-Block et al. 2019[158]<br>WA DNR 2020[159] |
| 2 | Species and genotypes may be maladapted to future climate. | Plant genotypes and species considered more tolerant of increased temperatures and changing disturbance regimes. | St. Clair et al. 2022[160]<br>NIACS 2022[161]<br>NIACS 2022[162] |
| 3 | Increasing temperatures and other stressors threaten urban forests. | Develop silvicultural techniques to maintain urban forests. | Piana et al. 2021[163]<br>Piana et al. 2021[164]<br>Pregitzer et al. 2019[165] |
| 4 | Climate change adaptation plans are not typically suited to the needs of Indigenous Peoples. | Develop a Tribal climate change adaptation menu to incorporate Tribal values and cultural considerations into climate adaptation planning. | Tribal Adaptation Menu Team 2019[166] |
| 5 | More frequent and severe flooding. | Relocate and restore recreation-related infrastructure in vulnerable floodplains. | NIACS 2022[167] |
| 6 | More intense hurricanes increasing downed and damaged trees. | Increase capacity to learn from disaster and manage vegetative debris in order to recover value and sequester carbon. | Álvarez-Berríos et al. 2021[168]<br>Wiener et al. 2020[169] |

Taking into account all lands and people improves climate change vulnerability assessments, because of the many federal, state, territorial, municipal, private, Tribal, and Indigenous management policies and practices governing forests. Adaptation options differ by region, ownership, and management objectives, reflecting differences in regional climate and ecology, management history, and local values. However, general principles for adaptation hold across geographies and ownerships and are consistent with the principles of sustainable forest management. For example, in drought-prone temperate forests, reducing tree densities increases resistance (the ability to remain largely unaltered by disturbance) and resilience (the ability to recover after disturbance) to bark beetles and drought[170,171] and, when combined with fuel reduction treatments (e.g., prescribed fire), resilience to wildfire.[145,146] In fire-prone forests, reintroducing low- to mixed-severity fire and incorporating Indigenous Knowledge into fire management can reduce the risk of high-severity wildfire and promote valued ecosystem services[172,173] (Table 7.1; KM 16.3). Promoting biological diversity is also a common adaptation strategy,[150] as forest areas of high diversity are better at maintaining ecosystem functions.[174] Increasing the diversity of functional traits, such as shade tolerance, seed size, specific leaf area, ability to resprout, and bark thickness, may give forests a better chance to adapt to climate-related disturbances.[174,175]

Opportunities to better integrate social considerations of climate-driven changes in forests and forest management are emerging, as socioecological vulnerability frameworks and assessments expand their treatment of social dimensions.[176,177] For example, assessments can consider ecological changes and altered ecosystem services in light of the socioeconomic characteristics (e.g., social vulnerability) and welfare of the beneficiaries of ecosystem services, including social capacity to adapt to novel conditions. Access to forests and associated ecosystem services, including recreation, differs from urban to rural settings and with socio-economic characteristics such as racial and ethnic identity. For example, Black landowners in the South face

a legacy of unequal access to forestry extension and management, as well as insecure property ownership and minimal economic return for land inherited without a will.[178] Environmental justice analyses can be used to consider access to forests, technical assistance for forest management, and ecosystem services, as well as hazardous occurrences such as wildfire smoke.[179,180]

Forest health and management are tied to socioeconomic well-being among Indigenous and Tribal Peoples, where stewardship of forest ecosystems is interrelated with cultural identity (KM 16.3).[181,182] Such perspectives lead to different adaptation options with emphasis on active management designed to maintain reciprocal relationships. For example, many Diné (Navajo) depend directly on the land for their livelihoods and cultural traditions, and forests provide social, cultural, spiritual, and economic resources. Under continued warming, substantial forest losses are projected for the Diné. Ambitious tree planting strategies have been proposed to offset these losses and meet future resource needs (e.g., for fuelwood; 50% of Diné households use wood as a primary heating source).[183]

Adapting reforestation practices, including where species are planted and which species and genotypes are planted, will facilitate adaptation to future climatic conditions. Assisted migration can help address the effects of climate change by promoting tree species and genotypes expected to survive future climates and disturbance regimes.[184] Assisted migration encompasses 1) assisted population migration within a species range, 2) assisted range expansion adjacent to a species range, and 3) assisted species migration that moves species far outside their range.[185] Specific guidance on assisted migration is rare, but tools such as hierarchical decision-making,[186] the Seedlot Selection Tool,[160] and the Managed Relocation Ecological Risk Assessment Tool[187] provide guidance.

Assisted migration and reforestation efforts are constrained by unreliable availability of climate-adapted seedling stock or other resources.[188] Adaptation interventions can focus on altering the exposure of forests to climate change or the demand for ecosystem services. Interventions include forest management that alters stand structures or composition, strengthening of disturbance response, and bolstering post-disturbance restoration.[189,190] Private forest owners' actions to adapt to climate change are socially, institutionally, and economically constrained (e.g., Andersson and Keskitalo 2018[191]); therefore, policy and market-based incentives have the potential to increase adaptation on private lands (e.g., Anderson et al. 2019[192]). Potential policies include regulations that require adaptation actions; subsidies (direct payments and tax reductions) that reduce private costs of actions or account for public benefits of private actions;[193] and taxes that increase the private costs of inaction or of actions that make forests less resilient to climate change (e.g., Hashida et al. 2020[194]). Given that future benefits from a private intervention are uncertain, subsidies (e.g., for hazardous fuels management) also reduce financial risks (e.g., Amacher et al. 2006[195]).

Effective implementation of climate adaptation requires working across landscapes with complex governances.[196] Equitable outcomes are enhanced by coproduction of knowledge (i.e., involving multiple knowledge sources and capacities from different groups of people) that determines expected risks, desired future benefits, and the capacity for implementing adaptation actions.[197]

# Traceable Accounts

## *Process Description*

Author selection centered on scientific expertise and ensuring that, to the extent possible, the author team represented a broad array of experiences. First, an outline of broad themes was developed by the chapter lead (CL) and federal coordinating lead author (CLA) based on review of previous assessments, a US Global Change Research Program (USGCRP) gap analysis, and new findings since the last National Climate Assessment.[11] The outline served as the basis for identifying the expertise necessary to complete the chapter. Next, the CL and CLA independently developed initial author lists following diversity criteria and guidance provided by USGCRP. It is important to note that prior to author selection, including the CL and CLA, the chapter was designated an all-federal-author chapter by the Federal Steering Committee, with the option to include non-federal authors as technical contributors. The CL and CLA relied heavily on the prepopulated list of individuals nominated through the USGCRP public call for authors to compile the initial author lists. The CL and CLA then worked through their initial lists of authors by chapter theme using the diversity criteria to arrive at the final list of chapter authors.

The author team met weekly to discuss chapter developments, comments, and timelines. Additional chapter authors and technical contributors were identified and added to increase depth and diversify perspectives. These decisions were informed by author team meetings, reviews and revisions, and comments received from US government agencies and the public. Consensus was built leveraging the specific expertise of chapter authors and by referring to the peer-reviewed literature, which was heavily weighted to articles published in the last five years. Engagement with the public occurred through a workshop held in January 2022 and opportunities for public review. Engagement with other chapters occurred through meetings among chapter leadership.

## Key Message 7.1

## Forests Are Increasingly Affected by Climate Change and Disturbances

### Description of Evidence Base

Abundant peer-reviewed literature indicates that climate change has increased the frequency, spatial scale, and severity of some disturbances that drive forest change.[56,198,199] Notable examples include area burned by wildfires in the West,[200] area burned by large wildfires in the West,[13] and area burned at high severity in the West.[18] Over half (55%) of the changes in fuel aridity in western US forests are attributable directly to climate change,[12] and relationships between wildfire and climate (low precipitation/drought or interactions between temperature and precipitation) explain the trends and most of the variation in area burned.[14,15,200,201] Projections of future wildfire[14,202] indicate climatic drivers, and forest responses are expected to differ with forest type and fuels, with the potential for fuel feedbacks to eventually limit increases in area burned (Kitzberger et al. 2017,[203] but see Abatzoglou et al. 2021[16]). There is also strong and increasing evidence that warming is reducing overwintering mortality and increasing voltinism (number of generations) of some bark beetles,[26,29,63] resulting in large impacts, especially in the West, and expansions of geographic and host ranges in both the Northeast and West.[26,63] In the Southwest, exceptional drought has compromised host tree defenses, resulting in increased bark beetle impacts.[58,60,61,204] Despite well-described physical changes to forest fuels following bark beetle outbreaks, effects on wildfires are mixed. These contradictions are largely explained by the different metrics used to assess wildfires, time since the outbreak, the spatial scale of studies, and the confounding effects of fire weather and beetle impacts.[66] Pathogens, extreme weather events (hurricanes, wind, flooding), and sea level rise have less evidence supporting widespread connections

between disturbance and climate, in part because attribution is difficult for phenomena that occur rarely. Continued warming and regional changes in precipitation are expected to amplify interactions among disturbance agents and further alter forest ecosystem structure and function. Evidence for shifts in tree species ranges as affected by climate change is available for some areas;[205,206,207] however, understory species range shifts will depend on whether the canopy is affected.[49,208]

### Major Uncertainties and Research Gaps

A major uncertainty is the role of climate-related disturbance in landscape transformation, or the permanent transition to a different vegetation type, perhaps non-forested. Projecting future forest changes and resulting effects on ecosystem services should be predicated on an ability to simulate and anticipate the (sometimes rapid) emergence of novel vegetation types. A key research gap is whether and how much management actions may alter climate-driven disturbance effects and resulting forest ecosystem trajectories. For example, differences in forest type and management history affect fuels available to fire and how climate changes alter their flammability or susceptibility to insects or other disturbances. As a result, forest-specific management may be capable of altering some or most of the projected climate effects, all other things being equal, primarily for wildfire. Another research gap is the ability to model the hydrological responses in forested watersheds under novel combinations of climate and disturbance.

### Description of Confidence and Likelihood

The vast majority of the scientific literature on forest disturbance supports a *high confidence* statement for the role of climate-related disturbance in structuring forest ecosystems, although estimates of the strength of relationships between climate and disturbance vary with mechanisms and methods. However, the mechanisms by which disturbances interact and the degrees to which they will chronically or acutely affect forests differ greatly with the type and nature of the disturbance. For example, interactions between wildfire and bark beetles are well documented and may be amplified over time, whereas interactions between drought and pathogens are poorly understood. Disturbances can rapidly alter forest structure and dynamics, as well as other resource values (e.g., recreation) and socioeconomic conditions. It is *likely* that such dynamics will continue, but it is difficult to project how much they will resemble the dynamics with which we have experience. Therefore, *high confidence* exists that future disturbances will further alter forest structure and function.

## Key Message 7.2

## Climate Change Affects Ecosystem Services Provided by Forests

### Description of Evidence Base

Abundant peer-reviewed literature underpins how climate change is affecting ecosystem services. Most research supports that increases in air temperature and changing precipitation patterns are reducing the capacity of US forests to sequester and store carbon, especially in the West.[3] There is also strong evidence that climate change is reducing snowpacks and decreasing water supplies in the West.[125] Stream temperatures are increasing in multiple regions, reducing coldwater fish habitat.[137,138] Increases in the frequency of large wildfires in the West reduce air and water quality[103,132,134,209,210] and, when combined with an expanding wildland–urban interface (WUI),[5] *likely* increase structure losses.

Climate change affects timber by increasing the area burned by wildfires[211] and by increasing the area affected by, and the severity of, bark beetle outbreaks,[26,58] leading to increased timber salvage and lower timber values. Beetle outbreaks have also lowered scenic beauty, property values, and property tax revenues for local governments in some areas.[100] Non-timber products in some parts of the US are increasingly

subjected to variable output, due to climate-related increases in disturbances and variability in temperatures and seasonality,[212] affecting benefits of cultural ecosystem services, particularly for Indigenous and Tribal Peoples.[90,213] For example, in the Midwest and Northeast, rising average winter temperatures and reduced snow depth have increased the severity of winter tick (*Dermacentor albipictus*) and brainworm (*Parelaphostrongylus tenuis*) infestations[214,215] in moose, increasing adult and calf mortality and reducing hunting opportunities.[216,217,218] Rising sea levels are leading to ghost forests, thereby changing recreation and affecting storm surge buffering capacity.[219,220] Sea level rise is also projected to exceed mangrove accretion rates in future decades, leading to loss of mangrove forests in many places.[38,39,40] In response to warmer winters, however, mangrove expansion is currently occurring along the US Gulf and Atlantic coasts, enhancing coastal protection from storms and rising seas, adding biomass carbon, improving pelican habitat, creating loss of coastal views, increasing insects, reducing fishing access, and reducing habitat for whooping cranes, an endangered species.[41] Skiing in undeveloped areas and motorized snow-based activities in the continental US are projected to be affected by climate change by midcentury, with effects varying by region, model scenario, and participation measure.[93,221]

## Major Uncertainties and Research Gaps

Climate change effects on recreation values are uncertain because human values change over time and because overall effects will depend on how temperature and precipitation patterns change across forested landscapes. Furthermore, imprecise information on historical recreation activities has led to a lack of statistical significances for quantitative estimates of how climate may be affecting particular activities. Research gaps exist regarding the effects of climate change on cultural goods and services important to Indigenous and Tribal Peoples in the US.

## Description of Confidence and Likelihood

Recent research provides ample evidence of the direct and indirect effects of climate change on forest ecosystem services. There is *high confidence* that multiple ecosystem services are being impacted by climate change, including coldwater fishing, multiple recreation activities, amenities from coastal forests lost to rising seas, Indigenous forest values, consumptive and nonconsumptive wildlife provisioning, and many nontimber forest products. There is *high confidence* that climate change is affecting forest carbon sequestration; the provisioning of clean water from forests; the occurrence of wildfires that destroy structures, alter habitats, and increase $PM_{2.5}$ concentrations in the atmosphere; and snowpacks in the West and Northeast. There is *medium confidence* that climate change is changing the availability of water-based and snow-based recreation. The capacity of forests to continue providing ecosystem services will be determined, in part, by changes in society and how those changes interact with future climate effects (*likely, high confidence*).

## Key Message 7.3

## Adaptation Actions Are Necessary for Maintaining Resilient Forest Ecosystems

### Description of Evidence Base

Climate change vulnerability assessments provide the basis for adaptation, and there are many examples of vulnerability assessments that have been conducted for a variety of forest landowners and managers in recent years. Although frameworks and examples of adaptation planning are still more numerous than adaptation actions, the recent literature contains an increasing number of adaptation actions implemented to increase forest resistance and resilience to climate change (Table 7.1). Research on climate change effects and adaptation efforts increasingly draws on coproduction, iterative, and collaborative processes that combine different types of knowledge and participants to produce effective climate adaptation science.[222]

Although considering local context and management objectives is critical in identifying climate change adaptation options, there are general principles applicable across forest types. Adaptation principles that receive strong support in the scientific literature include promoting diversity, modifying planting practices, implementing assisted migration, and increasing resilience to disturbance. A mixture of tree species and functional traits[223] in a forest stand increases the likelihood that disturbances, such as insect and disease outbreaks, will not result in complete stand mortality; that forests will be better able to withstand changing environmental conditions; and that multiple ecosystem services can be provided.[174,224] Strong and increasing evidence exists for lowering stand density in many fire-prone forest types to 1) increase resistance and resilience to disturbances, including droughts, bark beetles, and wildfires;[145,146,157,170,225] and 2) improve residual tree growth by decreasing fuel loads, decreasing tree competition, and increasing water availability.[225,226,227]

### Major Uncertainties and Research Gaps

Identification of climate change adaptation actions is based on our current understanding of ecosystem function and how management actions affect ecosystem function. However, understanding of the effectiveness of climate change adaptation actions is limited by a lack of long-term monitoring over several decades. Future monitoring will be critical for evaluating the effectiveness of adaptation actions in different contexts, especially because interactions among multiple disturbances could result in unexpected effects on ecosystems and their response to adaptation actions. Implementation of adaptation actions is still in the relatively early stages, and barriers to adaptation implementation are expected to persist, limiting the future pace, scale, and effectiveness of adaptation.

### Description of Confidence and Likelihood

There is *high confidence* that changes in climate over the last several decades are already affecting the ability of forest owners and managers to meet management objectives. This is primarily because of the increasing extent of severe disturbances, primarily wildfires, bark beetle outbreaks in the West, and storms in coastal locations in the East. This is based on the proliferation of peer-reviewed literature to support climate-informed management and planning, as well as various guidelines and sources of adaptation options developed by agencies and non-governmental organizations. Based on understanding of forest ecosystems and effects of management actions, there is *medium confidence* that adaptation actions will be effective in helping maintain the provisioning of ecosystem services. Continued monitoring is needed to assess the effectiveness of adaptation actions.

# References


1. Bonan, G.B., 2016: Forests, climate, and public policy: A 500-year interdisciplinary odyssey. *Annual Review of Ecology, Evolution, and Systematics*, **47** (1), 97–121. https://doi.org/10.1146/annurev-ecolsys-121415-032359

2. Oswalt, S.N., W.B. Smith, P.D. Miles, and S.A. Pugh, 2019: Forest Resources of the United States, 2017: A Technical Document Supporting the Forest Service 2020 RPA Assessment. Gen. Tech. Rep. WO-97. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 223 pp. https://doi.org/10.2737/wo-gtr-97

3. Domke, G.M., B.F. Walters, C.L. Giebink, E.J. Greenfield, J.E. Smith, M.C. Nichols, J.A. Knott, S.M. Ogle, J.W. Coulston, and J. Steller, 2023: Greenhouse Gas Emissions and Removals from Forest Land, Woodlands, Urban Trees, and Harvested Wood Products in the United States, 1990–2021. Resour. Bull. WO-101. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 10 pp. https://doi.org/10.2737/wo-rb-101

4. Zhang, Y., C. Song, T. Hwang, K. Novick, J.W. Coulston, J. Vose, M.P. Dannenberg, C.R. Hakkenberg, J. Mao, and C.E. Woodcock, 2021: Land cover change-induced decline in terrestrial gross primary production over the conterminous United States from 2001 to 2016. *Agricultural and Forest Meteorology*, **308–309**, 108609. https://doi.org/10.1016/j.agrformet.2021.108609

5. Mockrin, M.H., D. Helmers, S. Martinuzzi, T.J. Hawbaker, and V.C. Radeloff, 2022: Growth of the wildland-urban interface within and around U.S. National Forests and Grasslands, 1990–2010. *Landscape and Urban Planning*, **218**, 104283. https://doi.org/10.1016/j.landurbplan.2021.104283

6. AF&PA, 2022: Our Economic Impact. American Forest and Paper Association. https://www.afandpa.org/statistics-resources/our-economic-impact

7. Hartmann, H., A. Bastos, A.J. Das, A. Esquivel-Muelbert, W.M. Hammond, J. Martínez-Vilalta, N.G. McDowell, J.S. Powers, T.A.M. Pugh, K.X. Ruthrof, and C.D. Allen, 2022: Climate change risks to global forest health: Emergence of unexpected events of elevated tree mortality worldwide. *Annual Review of Plant Biology*, **73** (1), 673–702. https://doi.org/10.1146/annurev-arplant-102820-012804

8. Moser, S.C., J.A. Ekstrom, J. Kim, and S. Heitsch, 2019: Adaptation finance archetypes: Local governments' persistent challenges of funding adaptation to climate change and ways to overcome them. *Ecology and Society*, **24** (2), 28. https://doi.org/10.5751/es-10980-240228

9. USDA, 2022: Climate Resilience and Carbon Stewardship of America's National Forests and Grasslands. Secretary's Memorandum 1077-004. U.S. Department of Agriculture, Office of the Secretary, Washington, DC. https://www.usda.gov/directives/sm-1077-004

10. USDA, 2021: Action Plan for Climate Adaptation and Resilience. Departmental Regulation 1070-001. U.S. Department of Agriculture. https://www.sustainability.gov/pdfs/usda-2021-cap.pdf

11. Vose, J.M., D.L. Peterson, G.M. Domke, C.J. Fettig, L.A. Joyce, R.E. Keane, C.H. Luce, J.P. Prestemon, L.E. Band, J.S. Clark, N.E. Cooley, A. D'Amato, and J.E. Halofsky, 2018: Ch. 6. Forests. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 232–267. https://doi.org/10.7930/nca4.2018.ch6

12. Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (42), 11770–11775. https://doi.org/10.1073/pnas.1607171113

13. Dennison, P.E., S.C. Brewer, J.D. Arnold, and M.A. Moritz, 2014: Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters*, **41** (8), 2928–2933. https://doi.org/10.1002/2014gl059576

14. western United States: An ecological approach to nonstationarity. *Earth's Future*, **6** (8), 1097–1111. https://doi.org/10.1029/2018ef000878

15. Holden, Z.A., A. Swanson, C.H. Luce, W.M. Jolly, M. Maneta, J.W. Oyler, D.A. Warren, R. Parsons, and D. Affleck, 2018: Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (36), E8349–E8357. https://doi.org/10.1073/pnas.1802316115

16. Abatzoglou, J.T., D.S. Battisti, A.P. Williams, W.D. Hansen, B.J. Harvey, and C.A. Kolden, 2021: Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth & Environment*, **2** (1), 227. https://doi.org/10.1038/s43247-021-00299-0

17. Kennedy, M.C., R.R. Bart, C.L. Tague, and J.S. Choate, 2021: Does hot and dry equal more wildfire? Contrasting short- and long-term climate effects on fire in the Sierra Nevada, CA. *Ecosphere*, **12** (7), e03657. https://doi.org/10.1002/ecs2.3657

18. Parks, S.A. and J.T. Abatzoglou, 2020: Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters*, **47** (22), e2020GL089858. https://doi.org/10.1029/2020gl089858

19. Jones, M.W., J.T. Abatzoglou, S. Veraverbeke, N. Andela, G. Lasslop, M. Forkel, A.J.P. Smith, C. Burton, R.A. Betts, G.R. van der Werf, S. Sitch, J.G. Canadell, C. Santín, C. Kolden, S.H. Doerr, and C. Le Quéré, 2022: Global and regional trends and drivers of fire under climate change. *Reviews of Geophysics*, **60** (3), e2020RG000726. https://doi.org/10.1029/2020rg000726

20. Parks, S.A., C. Miller, J.T. Abatzoglou, L.M. Holsinger, M.-A. Parisien, and S.Z. Dobrowski, 2016: How will climate change affect wildland fire severity in the western US? *Environmental Research Letters*, **11** (3), 035002. https://doi.org/10.1088/1748-9326/11/3/035002

21. Jain, P., X. Wang, and M.D. Flannigan, 2017: Trend analysis of fire season length and extreme fire weather in North America between 1979 and 2015. *International Journal of Wildland Fire*, **26** (12), 1009–1020. https://doi.org/10.1071/wf17008

22. Abatzoglou, J.T., A.P. Williams, and R. Barbero, 2019: Global emergence of anthropogenic climate change in fire weather indices. *Geophysical Research Letters*, **46** (1), 326–336. https://doi.org/10.1029/2018gl080959

23. Balch, J.K., B.A. Bradley, J.T. Abatzoglou, R.C. Nagy, E.J. Fusco, and A.L. Mahood, 2017: Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (11), 2946–2951. https://doi.org/10.1073/pnas.1617394114

24. Chiodi, A.M., B.E. Potter, and N.K. Larkin, 2021: Multi-decadal change in western US nighttime vapor pressure deficit. *Geophysical Research Letters*, **48** (15), e2021GL092830. https://doi.org/10.1029/2021gl092830

25. Bailey, R.G., 2016: Bailey's Ecoregions and Subregions of the United States, Puerto Rico, and the U.S. Virgin Islands. U.S. Geological Survey, Forest Service Research Data Archive, Fort Collins, CO. https://doi.org/10.2737/RDS-2016-0003

26. Bentz, B.J., J. Régnière, C.J. Fettig, E.M. Hansen, J.L. Hayes, J.A. Hicke, R.G. Kelsey, J.F. Negrón, and S.J. Seybold, 2010: Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. *BioScience*, **60** (8), 602–613. https://doi.org/10.1525/bio.2010.60.8.6

27. Fettig, C.J., C. Asaro, J.T. Nowak, K.J. Dodds, K.J.K. Gandhi, J.E. Moan, and J. Robert, 2022: Trends in bark beetle impacts in North America during a period (2000–2020) of rapid environmental change. *Journal of Forestry*, **120** (6), 693–713. https://doi.org/10.1093/jofore/fvac021

28. O'Connor, C.D., A.M. Lynch, D.A. Falk, and T.W. Swetnam, 2015: Post-fire forest dynamics and climate variability affect spatial and temporal properties of spruce beetle outbreaks on a Sky Island mountain range. *Forest Ecology and Management*, **336**, 148–162. https://doi.org/10.1016/j.foreco.2014.10.021

29. Robbins, Z.J., C. Xu, B.H. Aukema, P.C. Buotte, R. Chitra-Tarak, C.J. Fettig, M.L. Goulden, D.W. Goodsman, A.D. Hall, C.D. Koven, L.M. Kueppers, G.D. Madakumbura, L.A. Mortenson, J.A. Powell, and R.M. Scheller, 2022: Warming increased bark beetle-induced tree mortality by 30% during an extreme drought in California. *Global Change Biology*, **28** (2), 509–523. https://doi.org/10.1111/gcb.15927

30. Dudney, J., C.E. Willing, A.J. Das, A.M. Latimer, J.C.B. Nesmith, and J.J. Battles, 2021: Nonlinear shifts in infectious rust disease due to climate change. *Nature Communications*, **12** (1), 5102. https://doi.org/10.1038/s41467-021-25182-6

31. Finch, D.M., J.L. Butler, J.B. Runyon, C.J. Fettig, F.F. Kilkenny, S. Jose, S.J. Frankel, S.A. Cushman, R.C. Cobb, J.S. Dukes, J.A. Hicke, and S.K. Amelon, 2021: Ch. 4. Effects of climate change on invasive species. In: *Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector*. Poland, T.M., T. Patel-Weynand, D.M. Finch, C.F. Miniat, D.C. Hayes, and V.M. Lopez, Eds. Springer, Cham, Switzerland, 57–83. https://doi.org/10.1007/978-3-030-45367-1_4

32. Trauernicht, C., E. Pickett, C.P. Giardina, C.M. Litton, S. Cordell, and A. Beavers, 2015: The contemporary scale and context of wildfire in Hawai'i. *Pacific Science*, **69** (4), 427–444. https://doi.org/10.2984/69.4.1

33. Hickman, J.E. and M.T. Lerdau, 2013: Biogeochemical impacts of the northward expansion of kudzu under climate change: The importance of ecological context. *Ecosphere*, **4** (10), art121. https://doi.org/10.1890/es13-00142.1

34. Anderson-Teixeira, K.J., A.D. Miller, J.E. Mohan, T.W. Hudiburg, B.D. Duval, and E.H. DeLucia, 2013: Altered dynamics of forest recovery under a changing climate. *Global Change Biology*, **19** (7), 2001–2021. https://doi.org/10.1111/gcb.12194

35. Matthews, E.R., J.P. Schmit, and J.P. Campbell, 2016: Climbing vines and forest edges affect tree growth and mortality in temperate forests of the U.S. Mid-Atlantic States. *Forest Ecology and Management*, **374**, 166–173. https://doi.org/10.1016/j.foreco.2016.05.005

36. Hammond, W.M., A.P. Williams, J.T. Abatzoglou, H.D. Adams, T. Klein, R. López, C. Sáenz-Romero, H. Hartmann, D.D. Breshears, and C.D. Allen, 2022: Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. *Nature Communications*, **13** (1), 1761. https://doi.org/10.1038/s41467-022-29289-2

37. Grieger, R., S.J. Capon, W.L. Hadwen, and B. Mackey, 2020: Between a bog and a hard place: A global review of climate change effects on coastal freshwater wetlands. *Climatic Change*, **163** (1), 161–179. https://doi.org/10.1007/s10584-020-02815-1

38. Saintilan, N., N.S. Khan, E. Ashe, J.J. Kelleway, K. Rogers, C.D. Woodroffe, and B.P. Horton, 2020: Thresholds of mangrove survival under rapid sea level rise. *Science*, **368** (6495), 1118–1121. https://doi.org/10.1126/science.aba2656

39. Sasmito, S.D., D. Murdiyarso, D.A. Friess, and S. Kurnianto, 2016: Can mangroves keep pace with contemporary sea level rise? A global data review. *Wetlands Ecology and Management*, **24** (2), 263–278. https://doi.org/10.1007/s11273-015-9466-7

40. Ward, R.D., D.A. Friess, R.H. Day, and R.A. Mackenzie, 2016: Impacts of climate change on mangrove ecosystems: A region by region overview. *Ecosystem Health and Sustainability*, **2** (4), e01211. https://doi.org/10.1002/ehs2.1211

41. Osland, M.J., A.R. Hughes, A.R. Armitage, S.B. Scyphers, J. Cebrian, S.H. Swinea, C.C. Shepard, M.S. Allen, L.C. Feher, J.A. Nelson, C.L. O'Brien, Colt R. Sanspree, D.L. Smee, C.M. Snyder, A.P. Stetter, Philip W. Stevens, K.M. Swanson, L.H. Williams, Janell M. Brush, J. Marchionno, and R. Bardou, 2022: The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: Current understanding, knowledge gaps, and emerging research needs. *Global Change Biology*, **28** (10), 3163–3187. https://doi.org/10.1111/gcb.16111

42. Hagmann, R.K., P.F. Hessburg, S.J. Prichard, N.A. Povak, P.M. Brown, P.Z. Fulé, R.E. Keane, E.E. Knapp, J.M. Lydersen, K.L. Metlen, M.J. Reilly, A.J. Sánchez Meador, S.L. Stephens, J.T. Stevens, A.H. Taylor, L.L. Yocom, M.A. Battaglia, D.J. Churchill, L.D. Daniels, D.A. Falk, P. Henson, J.D. Johnston, M.A. Krawchuk, C.R. Levine, G.W. Meigs, A.G. Merschel, M.P. North, H.D. Safford, T.W. Swetnam, and A.E.M. Waltz, 2021: Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecological Applications*, **31** (8), e02431. https://doi.org/10.1002/eap.2431

43. Falk, D.A., P.J. van Mantgem, J.E. Keeley, R.M. Gregg, C.H. Guiterman, A.J. Tepley, D. Jn Young, and L.A. Marshall, 2022: Mechanisms of forest resilience. *Forest Ecology and Management*, **512**, 120129. https://doi.org/10.1016/j.foreco.2022.120129

44. Stanke, H., A.O. Finley, G.M. Domke, A.S. Weed, and D.W. MacFarlane, 2021: Over half of western United States' most abundant tree species in decline. *Nature Communications*, **12** (1), 451. https://doi.org/10.1038/s41467-020-20678-z

45. Crausbay, S.D., H.R. Sofaer, A.E. Cravens, B.C. Chaffin, K.R. Clifford, J.E. Gross, C.N. Knapp, D.J. Lawrence, D.R. Magness, A.J. Miller-Rushing, G.W. Schuurman, and C.S. Stevens-Rumann, 2022: A science agenda to inform natural resource management decisions in an era of ecological transformation. *BioScience*, **72** (1), 71–90. https://doi.org/10.1093/biosci/biab102

46. Davis, K.T., S.Z. Dobrowski, P.E. Higuera, Z.A. Holden, T.T. Veblen, M.T. Rother, S.A. Parks, A. Sala, and M.P. Maneta, 2019: Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6193–6198. https://doi.org/10.1073/pnas.1815107116

47. Keeley, J.E., P. van Mantgem, and D.A. Falk, 2019: Fire, climate and changing forests. *Nature Plants*, **5** (8), 774–775. https://doi.org/10.1038/s41477-019-0485-x

48. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.001

49. Spicer, M.E., H.V.N. Radhamoni, M.C. Duguid, S.A. Queenborough, and L.S. Comita, 2022: Herbaceous plant diversity in forest ecosystems: Patterns, mechanisms, and threats. *Plant Ecology*, **223** (2), 117–129. https://doi.org/10.1007/s11258-021-01202-9

50. Ash, J.D., T.J. Givnish, and D.M. Waller, 2017: Tracking lags in historical plant species' shifts in relation to regional climate change. *Global Change Biology*, **23** (3), 1305–1315. https://doi.org/10.1111/gcb.13429

51. Harrison, S., E.I. Damschen, and J.B. Grace, 2010: Ecological contingency in the effects of climatic warming on forest herb communities. *Proceedings of the National Academy of Sciences of the United States of America*, **107** (45), 19362–19367. https://doi.org/10.1073/pnas.1006823107

52. Cansler, C.A., V.R. Kane, P.F. Hessburg, J.T. Kane, S.M.A. Jeronimo, J.A. Lutz, N.A. Povak, D.J. Churchill, and A.J. Larson, 2022: Previous wildfires and management treatments moderate subsequent fire severity. *Forest Ecology and Management*, **504**, 119764. https://doi.org/10.1016/j.foreco.2021.119764

53. Larson, A.J., S.M.A. Jeronimo, P.F. Hessburg, J.A. Lutz, N.A. Povak, C.A. Cansler, V.R. Kane, and D.J. Churchill, 2022: Tamm review: Ecological principles to guide post-fire forest landscape management in the inland Pacific and northern Rocky Mountain regions. *Forest Ecology and Management*, **504**, 119680. https://doi.org/10.1016/j.foreco.2021.119680

54. Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, R.E. Keane, L.N. Kobziar, C.A. Kolden, M. North, S.A. Parks, H.D. Safford, J.T. Stevens, L.L. Yocom, D.J. Churchill, R.W. Gray, D.W. Huffman, F.K. Lake, and P. Khatri-Chhetri, 2021: Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications*, **31** (8), e02433. https://doi.org/10.1002/eap.2433

55. Sonti, N.F., R. Riemann, M.H. Mockrin, and G.M. Domke, 2023: Expanding wildland-urban interface alters forest structure and landscape context in the northern United States. *Environmental Research Letters*, **18** (1), 014010. https://doi.org/10.1088/1748-9326/aca77b

56. Hagmann, R.K., P.F. Hessburg, R.B. Salter, A.G. Merschel, and M.J. Reilly, 2022: Contemporary wildfires further degrade resistance and resilience of fire-excluded forests. *Forest Ecology and Management*, **506**, 119975. https://doi.org/10.1016/j.foreco.2021.119975

57. O'Connor, C.D., D.A. Falk, and G.M. Garfin, 2020: Projected climate-fire interactions drive forest to shrubland transition on an Arizona Sky Island. *Frontiers in Environmental Science*, **8**, 137. https://doi.org/10.3389/fenvs.2020.00137

58. Kolb, T.E., C.J. Fettig, M.P. Ayres, B.J. Bentz, J.A. Hicke, R. Mathiasen, J.E. Stewart, and A.S. Weed, 2016: Observed and anticipated impacts of drought on forest insects and diseases in the United States. *Forest Ecology and Management*, **380**, 321–334. https://doi.org/10.1016/j.foreco.2016.04.051

59. Hansen, E.M. and B.J. Bentz, 2003: Comparison of reproductive capacity among univoltine, semivoltine, and re-emerged parent spruce beetles (Coleoptera: Scolytidae). *The Canadian Entomologist*, **135** (5), 697–712. https://doi.org/10.4039/n02-109

60. Fettig, C.J., L.A. Mortenson, B.M. Bulaon, and P.B. Foulk, 2019: Tree mortality following drought in the central and southern Sierra Nevada, California, U.S. *Forest Ecology and Management*, **432**, 164–178. https://doi.org/10.1016/j.foreco.2018.09.006

61. Koontz, M.J., A.M. Latimer, L.A. Mortenson, C.J. Fettig, and M.P. North, 2021: Cross-scale interaction of host tree size and climatic water deficit governs bark beetle-induced tree mortality. *Nature Communications*, **12** (1), 129. https://doi.org/10.1038/s41467-020-20455-y

62. Robbins, Z.J., C. Xu, A. Jonko, R. Chitra-Tarak, C.J. Fettig, J. Costanza, L.A. Mortenson, B.H. Aukema, L.M. Kueppers, and R.M. Scheller, 2023: Carbon stored in live ponderosa pines in the Sierra Nevada will not return to pre-drought (2012) levels during the 21st century due to bark beetle outbreaks. *Frontiers in Environmental Science*, **11**, 1112756. https://doi.org/10.3389/fenvs.2023.1112756

63. Dodds, K.J., C.F. Aoki, A. Arango-Velez, J. Cancelliere, A.W. D'Amato, M.F. DiGirolomo, and R.J. Rabaglia, 2018: Expansion of southern pine beetle into northeastern forests: Management and impact of a primary bark beetle in a new region. *Journal of Forestry*, **116** (2), 178–191. https://doi.org/10.1093/jofore/fvx009

64. Miller, L.K. and R.A. Werner, 1987: Cold-hardiness of adult and larval spruce beetles *Dendroctonus rufipennis* (Kirby) in interior Alaska. *Canadian Journal of Zoology*, **65** (12), 2927–2930. https://doi.org/10.1139/z87-444

65. Morris, J.L., S. Cottrell, C.J. Fettig, R.J. DeRose, K.M. Mattor, V.A. Carter, J. Clear, J. Clement, W.D. Hansen, J.A. Hicke, P.E. Higuera, A.W. Seddon, H. Seppä, R.L. Sherriff, J.D. Stednick, and S.J. Seybold, 2018: Bark beetles as agents of change in social–ecological systems. *Frontiers in Ecology and the Environment*, **16** (S1), S34–S43. https://doi.org/10.1002/fee.1754

66. Fettig, C.J., J.B. Runyon, C.S. Homicz, P.M.A. James, and M.D. Ulyshen, 2022: Fire and insect interactions in North American forests. *Current Forestry Reports*, **8**, 301–316. https://doi.org/10.1007/s40725-022-00170-1

67. Runyon, J.B., C.J. Fettig, J.A. Trilling, A.S. Munson, L.A. Mortenson, B.E. Steed, K.E. Gibson, C.L. Jørgensen, S.R. McKelvey, J.D. McMillin, J.P. Audley, and J.F. Negrón, 2020: Changes in understory vegetation including invasive weeds following mountain pine beetle outbreaks. *Trees, Forests and People*, **2**, 100038. https://doi.org/10.1016/j.tfp.2020.100038

68. Kleinman, J.S., J.D. Goode, A.C. Fries, and J.L. Hart, 2019: Ecological consequences of compound disturbances in forest ecosystems: A systematic review. *Ecosphere*, **10** (11), e02962. https://doi.org/10.1002/ecs2.2962

69. Raymond, C., R.M. Horton, J. Zscheischler, O. Martius, A. AghaKouchak, J. Balch, S.G. Bowen, S.J. Camargo, J. Hess, K. Kornhuber, M. Oppenheimer, A.C. Ruane, T. Wahl, and K. White, 2020: Understanding and managing connected extreme events. *Nature Climate Change*, **10** (7), 611–621. https://doi.org/10.1038/s41558-020-0790-4

70. Tian, X., B. Sohngen, J.B. Kim, S. Ohrel, and J. Cole, 2016: Global climate change impacts on forests and markets. *Environmental Research Letters*, **11** (3), 035011. https://doi.org/10.1088/1748-9326/11/3/035011

71. Johnston, C.M.T. and V.C. Radeloff, 2019: Global mitigation potential of carbon stored in harvested wood products. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (29), 14526–14531. https://doi.org/10.1073/pnas.1904231116

72. Anderegg, W.R.L., A.T. Trugman, G. Badgley, C.M. Anderson, A. Bartuska, P. Ciais, D. Cullenward, C.B. Field, J. Freeman, S.J. Goetz, J.A. Hicke, D. Huntzinger, R.B. Jackson, J. Nickerson, S. Pacala, and J.T. Randerson, 2020: Climate-driven risks to the climate mitigation potential of forests. *Science*, **368** (6497), 7005. https://doi.org/10.1126/science.aaz7005

73. Creutzburg, M.K., R.M. Scheller, M.S. Lucash, S.D. LeDuc, and M.G. Johnson, 2017: Forest management scenarios in a changing climate: Trade-offs between carbon, timber, and old forest. *Ecological Applications*, **27** (2), 503–518. https://doi.org/10.1002/eap.1460

74. Nepal, P., J.P. Prestemon, L.A. Joyce, and K.E. Skog, 2022: Global forest products markets and forest sector carbon impacts of projected sea level rise. *Global Environmental Change*, **77**, 102611. https://doi.org/10.1016/j.gloenvcha.2022.102611

75. Comerford, D.P., P.G. Schaberg, P.H. Templer, A.M. Socci, J.L. Campbell, and K.F. Wallin, 2013: Influence of experimental snow removal on root and canopy physiology of sugar maple trees in a northern hardwood forest. *Oecologia*, **171** (1), 261–269. https://doi.org/10.1007/s00442-012-2393-x

76. Sanders-DeMott, R., J.L. Campbell, P.M. Groffman, L.E. Rustad, and P.H. Templer, 2019: Ch. 10. Soil warming and winter snowpacks: Implications for northern forest ecosystem functioning. In: *Ecosystem Consequences of Soil Warming*. Mohan, J.E., Ed. Academic Press, 245–278. https://doi.org/10.1016/b978-0-12-813493-1.00011-9

77. Slatyer, R.A., K.D.L. Umbers, and P.A. Arnold, 2022: Ecological responses to variation in seasonal snow cover. *Conservation Biology*, **36** (1), e13727. https://doi.org/10.1111/cobi.13727

78. Sorensen, P.O., A.C. Finzi, M.-A. Giasson, A.B. Reinmann, R. Sanders-DeMott, and P.H. Templer, 2018: Winter soil freeze-thaw cycles lead to reductions in soil microbial biomass and activity not compensated for by soil warming. *Soil Biology and Biochemistry*, **116**, 39–47. https://doi.org/10.1016/j.soilbio.2017.09.026

79. Sorensen, P.O., P.H. Templer, and A.C. Finzi, 2016: Contrasting effects of winter snowpack and soil frost on growing season microbial biomass and enzyme activity in two mixed-hardwood forests. *Biogeochemistry*, **128** (1), 141–154. https://doi.org/10.1007/s10533-016-0199-3

80. Fei, S., S.N. Kivlin, G.M. Domke, I. Jo, E.A. LaRue, and R.P. Phillips, 2022: Coupling of plant and mycorrhizal fungal diversity: Its occurrence, relevance, and possible implications under global change. *New Phytologist*, **234** (6), 1960–1966. https://doi.org/10.1111/nph.17954

81. Dangremond, E.M., C.H. Hill, S. Louaibi, and I. Muñoz, 2022: Phenological responsiveness and fecundity decline near the southern range limit of *Trientalis borealis* (Primulaceae). *Plant Ecology*, **223** (1), 41–52. https://doi.org/10.1007/s11258-021-01190-w

82. Whyte, K., 2018: Settler colonialism, ecology, and environmental injustice. *Environment and Society*, **9** (1), 125–144. https://doi.org/10.3167/ares.2018.090109

83. Durglo, M., R.G. Everett, T. Incashola, M.I. McCarthy, S.H. Pete, J.M. Rosenau, T. Smith, S. Trahan, and A.A. Carlson, 2022: Ch. 7. Sčiłpálqʷ: Biocultural restoration of whitebark pine on the Flathead Reservation. In: *Climate Actions*. CRC Press, 34. https://doi.org/10.1201/9781003048701

84. Hitt, N.P., E.L. Snook, and D.L. Massie, 2017: Brook trout use of thermal refugia and foraging habitat influenced by brown trout. *Canadian Journal of Fisheries and Aquatic Sciences*, **74** (3), 406–418. https://doi.org/10.1139/cjfas-2016-0255

85. Isaak, D.J., C.H. Luce, D.L. Horan, G.L. Chandler, S.P. Wollrab, and D.E. Nagel, 2018: Global warming of salmon and trout rivers in the northwestern U.S.: Road to ruin or path through purgatory? *Transactions of the American Fisheries Society*, **147** (3), 566–587. https://doi.org/10.1002/tafs.10059

86. Redmond, M.D., F. Forcella, and N.N. Barger, 2012: Declines in pinyon pine cone production associated with regional warming. *Ecosphere*, **3** (12), 1–14. https://doi.org/10.1890/es12-00306.1

87. Voggesser, G., K. Lynn, J. Daigle, F.K. Lake, and D. Ranco, 2013: Cultural impacts to tribes from climate change influences on forests. *Climatic Change*, **120** (3), 615–626. https://doi.org/10.1007/s10584-013-0733-4

88. Fish and Wildlife Service, 2022: Endangered and threatened wildlife and plants; threatened species status with section 4(d) rule for whitebark pine (*Pinus albicaulis*). *Federal Register*, **87** (240), 76882–76917. https://www.govinfo.gov/content/pkg/FR-2022-12-15/pdf/2022-27087.pdf

89. Lynn, K., J. Daigle, J. Hoffman, F. Lake, N. Michelle, D. Ranco, C. Viles, G. Voggesser, and P. Williams, 2014: Ch. 4. The impacts of climate change on tribal traditional foods. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., B. Colombi, and R. Pandya, Eds. Springer, Cham, Switzerland, 37–48. https://doi.org/10.1007/978-3-319-05266-3_4

90. Mucioki, M., J. Sowerwine, D. Sarna-Wojcicki, F.K. Lake, and S. Bourque, 2021: Conceptualizing Indigenous Cultural Ecosystem Services (ICES) and benefits under changing climate conditions in the Klamath River Basin and their implications for land management and governance. *Journal of Ethnobiology*, **41** (3), 313–330. https://doi.org/10.2993/0278-0771-41.3.313

91. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

92. Askew, A.E. and J.M. Bowker, 2018: Impacts of climate change on outdoor recreation participation: Outlook to 2060. *The Journal of Park and Recreation Administration*, **36** (2), 97–120. https://doi.org/10.18666/jpra-2018-v36-i2-8316

93. Miller, A.B., P.L. Winter, J.J. Sánchez, D.L. Peterson, and J.W. Smith, 2022: Climate change and recreation in the western United States: Effects and opportunities for adaptation. *Journal of Forestry*, **120** (4), 453–472. https://doi.org/10.1093/jofore/fvab072

94. Wang, D., D. Guan, S. Zhu, M.M. Kinnon, G. Geng, Q. Zhang, H. Zheng, T. Lei, S. Shao, P. Gong, and S.J. Davis, 2021: Economic footprint of California wildfires in 2018. *Nature Sustainability*, **4** (3), 252–260. https://doi.org/10.1038/s41893-020-00646-7

95. EPA, 2021: Comparative Assessment of the Impacts of Prescribed Fire Versus Wildfire (CAIF): A Case Study in the Western U.S. EPA/600/R-21/197. U.S. Environmental Protection Agency, Washington, DC. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=352824

96. Jones, C.G., A.G. Rappold, J. Vargo, W.E. Cascio, M. Kharrazi, B. McNally, and S. Hoshiko, 2020: Out-of-hospital cardiac arrests and wildfire-related particulate matter during 2015–2017 California wildfires. *Journal of the American Heart Association*, **9** (8), e014125. https://doi.org/10.1161/jaha.119.014125

97. Boaggio, K., S.D. LeDuc, R.B. Rice, P.F. Duffney, K.M. Foley, A.L. Holder, S. McDow, and C.P. Weaver, 2022: Beyond particulate matter mass: Heightened levels of lead and other pollutants associated with destructive fire events in California. *Environmental Science & Technology*, **56** (20), 14272–14283. https://doi.org/10.1021/acs.est.2c02099

98. Proctor, C.R., J. Lee, D. Yu, A.D. Shah, and A.J. Whelton, 2020: Wildfire caused widespread drinking water distribution network contamination. AWWA *Water Science*, **2** (4), e1183. https://doi.org/10.1002/aws2.1183

99. Nadeau, M.S., N.J. DeCesare, D.G. Brimeyer, E.J. Bergman, R.B. Harris, K.R. Hersey, K.K. Huebner, P.E. Matthews, and T.P. Thomas, 2017: Status and trends of moose populations and hunting opportunity in the western United States. *Alces: A Journal Devoted to the Biology and Management of Moose*, **53**, 99–112. https://alcesjournal.org/index.php/alces/article/view/182

100. Cohen, J., C.E. Blinn, K.J. Boyle, T.P. Holmes, and K. Moeltner, 2016: Hedonic valuation with translating amenities: Mountain pine beetles and host trees in the Colorado Front Range. *Environmental and Resource Economics*, **63** (3), 613–642. https://doi.org/10.1007/s10640-014-9856-y

101. Marcano-Vega, H., 2020: U.S. Virgin Islands Forests, 2014. Resour. Bull. SRS 227. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 54 pp. https://doi.org/10.2737/srs-rb-227

102. Lugo, A.E., J.E. Smith, K.M. Potter, H. Marcano Vega, and C.M. Kurtz, 2022: The Contribution of Nonnative Tree Species to the Structure and Composition of Forests in the Conterminous United States in Comparison with Tropical Islands in the Pacific and Caribbean. Gen. Tech. Rep. IITF-54. U.S. Department of Agriculture, Forest Service, International Institute of Tropical Forestry, Río Piedras, PR, 81 pp. https://doi.org/10.2737/iitf-gtr-54

103. Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara, 2021: The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2011048118. https://doi.org/10.1073/pnas.2011048118

104. Maxwell, S.L., N. Butt, M. Maron, C.A. McAlpine, S. Chapman, A. Ullmann, D.B. Segan, and J.E.M. Watson, 2019: Conservation implications of ecological responses to extreme weather and climate events. *Diversity and Distributions*, **25** (4), 613–625. https://doi.org/10.1111/ddi.12878

105. Halsch, C.A., A.M. Shapiro, J.A. Fordyce, C.C. Nice, J.H. Thorne, D.P. Waetjen, and M.L. Forister, 2021: Insects and recent climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2002543117. https://doi.org/10.1073/pnas.2002543117

106. Wagner, D.L., E.M. Grames, M.L. Forister, M.R. Berenbaum, and D. Stopak, 2021: Insect decline in the Anthropocene: Death by a thousand cuts. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2023989118. https://doi.org/10.1073/pnas.2023989118

107. Reed, K.A., A.M. Stansfield, M.F. Wehner, and C.M. Zarzycki, 2020: Forecasted attribution of the human influence on Hurricane Florence. *Science Advances*, **6** (1), 9253. https://doi.org/10.1126/sciadv.aaw9253

108. Trenberth, K.E., L. Cheng, P. Jacobs, Y. Zhang, and J. Fasullo, 2018: Hurricane Harvey links to ocean heat content and climate change adaptation. *Earth's Future*, **6** (5), 730–744. https://doi.org/10.1029/2018ef000825

109. Sobel, A.H., A.A. Wing, S.J. Camargo, C.M. Patricola, G.A. Vecchi, C.-Y. Lee, and M.K. Tippett, 2021: Tropical cyclone frequency. *Earth's Future*, **9** (12), e2021EF002275. https://doi.org/10.1029/2021ef002275

110. Brown, D.R., T.W. Sherry, and J. Harris, 2011: Hurricane Katrina impacts the breeding bird community in a bottomland hardwood forest of the Pearl River Basin, Louisiana. *Forest Ecology and Management*, **261** (1), 111–119. https://doi.org/10.1016/j.foreco.2010.09.038

111. Pan, Y., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, A. Shvidenko, S.L. Lewis, J.G. Canadell, P. Ciais, R.B. Jackson, S.W. Pacala, A.D. McGuire, S. Piao, A. Rautiainen, S. Sitch, and D. Hayes, 2011: A large and persistent carbon sink in the world's forests. *Science*, **333** (6045), 988–993. https://doi.org/10.1126/science.1201609

112. Domke, G., C.A. Williams, R. Birdsey, J. Coulston, A. Finzi, C. Gough, B. Haight, J. Hicke, M. Janowiak, B.d. Jong, W.A. Kurz, M. Lucash, S. Ogle, M. Olguín-Álvarez, Y. Pan, M. Skutsch, C. Smyth, C. Swanston, P. Templer, D. Wear, and C.W. Woodall, 2018: Ch. 9. Forests. In: *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*. Cavallaro, N., G. Shrestha, R. Birdsey, M.A. Mayes, R.G. Najjar, S.C. Reed, P. Romero-Lankao, and Z. Zhu, Eds. U.S. Global Change Research Program, Washington, DC, USA, 365-398. https://doi.org/10.7930/SOCCR2.2018.Ch9

113. Harris, N.L., S.C. Hagen, S.S. Saatchi, T.R.H. Pearson, C.W. Woodall, G.M. Domke, B.H. Braswell, B.F. Walters, S. Brown, W. Salas, A. Fore, and Y. Yu, 2016: Attribution of net carbon change by disturbance type across forest lands of the conterminous United States. *Carbon Balance and Management*, **11** (1), 24. https://doi.org/10.1186/s13021-016-0066-5

114. Quirion, B.R., G.M. Domke, B.F. Walters, G.M. Lovett, J.E. Fargione, L. Greenwood, K. Serbesoff-King, J.M. Randall, and S. Fei, 2021: Insect and disease disturbances correlate with reduced carbon sequestration in forests of the contiguous United States. *Frontiers in Forests and Global Change*, **4**, 716582. https://doi.org/10.3389/ffgc.2021.716582

115. Sleeter, B.M., L. Frid, B. Rayfield, C. Daniel, Z. Zhu, and D.C. Marvin, 2022: Operational assessment tool for forest carbon dynamics for the United States: A new spatially explicit approach linking the LUCAS and CBM-CFS3 models. *Carbon Balance and Management*, **17** (1), 1. https://doi.org/10.1186/s13021-022-00201-1

116. Zhou, Q., G. Xian, J. Horton, D. Wellington, G. Domke, R. Auch, C. Li, and Z. Zhu, 2022: Tree regrowth duration map from LCMAP collection 1.0 land cover products in the conterminous United States, 1985–2017. *GIScience & Remote Sensing*, **59** (1), 959–974. https://doi.org/10.1080/15481603.2022.2083790

117. Law, B.E., T.W. Hudiburg, L.T. Berner, J.J. Kent, P.C. Buotte, and M.E. Harmon, 2018: Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (14), 3663–3668. https://doi.org/10.1073/pnas.1720064115

118. Fitts, L.A., M.B. Russell, G.M. Domke, and J.K. Knight, 2021: Modeling land use change and forest carbon stock changes in temperate forests in the United States. *Carbon Balance and Management*, **16** (1), 20. https://doi.org/10.1186/s13021-021-00183-6

119. Ameray, A., Y. Bergeron, O. Valeria, M. Montoro Girona, and X. Cavard, 2021: Forest carbon management: A review of silvicultural practices and management strategies across boreal, temperate and tropical forests. *Current Forestry Reports*, **7** (4), 245–266. https://doi.org/10.1007/s40725-021-00151-w

120. Law, B.E., W.R. Moomaw, T.W. Hudiburg, W.H. Schlesinger, J.D. Sterman, and G.M. Woodwell, 2022: Creating strategic reserves to protect forest carbon and reduce biodiversity losses in the United States. *Land*, **11** (5). https://doi.org/10.3390/land11050721

121. Littlefield, C.E. and A.W. D'Amato, 2022: Identifying trade-offs and opportunities for forest carbon and wildlife using a climate change adaptation lens. *Conservation Science and Practice*, **4** (4), e12631. https://doi.org/10.1111/csp2.12631

122. Ontl, T.A., M.K. Janowiak, C.W. Swanston, J. Daley, S. Handler, M. Cornett, S. Hagenbuch, C. Handrick, L. McCarthy, and N. Patch, 2020: Forest management for carbon sequestration and climate adaptation. *Journal of Forestry*, **118** (1), 86–101. https://doi.org/10.1093/jofore/fvz062

123. Cohen, E., G. Sun, L. Zhang, P. Caldwell, and S. Krieger, 2017: Quantifying the Role of Forested Lands in Providing Surface Drinking Water Supply for Puerto Rico. Gen. Tech. Rep. SRS-197-Addendum. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 20 pp. https://www.fs.usda.gov/research/treesearch/54732

124. Liu, N., G.R. Dobbs, P.V. Caldwell, C.F. Miniat, G. Sun, K. Duan, S.A.C. Nelson, P.V. Bolstad, and C.P. Carlson, 2022: Inter-basin transfers extend the benefits of water from forests to population centers across the conterminous U.S. *Water Resources Research*, **58** (5), e2021WR031537. https://doi.org/10.1029/2021wr031537

125. Mote, P.W., S. Li, D.P. Lettenmaier, M. Xiao, and R. Engel, 2018: Dramatic declines in snowpack in the western US. *Npj Climate and Atmospheric Science*, **1** (1), 1–6. https://doi.org/10.1038/s41612-018-0012-1

126. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. https://doi.org/10.1038/s41558-022-01290-z

127. Peterson, T.C., R.R. Heim, R. Hirsch, D.P. Kaiser, H. Brooks, N.S. Diffenbaugh, R.M. Dole, J.P. Giovannettone, K. Guirguis, T.R. Karl, R.W. Katz, K. Kunkel, D. Lettenmaier, G.J. McCabe, C.J. Paciorek, K.R. Ryberg, S. Schubert, V.B.S. Silva, B.C. Stewart, A.V. Vecchia, G. Villarini, R.S. Vose, J. Walsh, M. Wehner, D. Wolock, K. Wolter, C.A. Woodhouse, and D. Wuebbles, 2013: Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge. *Bulletin of the American Meteorological Society*, **94** (6), 821–834. https://doi.org/10.1175/bams-d-12-00066.1

128. Yochum, S.E., J.A. Scott, and D.H. Levinson, 2019: Methods for assessing expected flood potential and variability: Southern Rocky Mountains region. *Water Resources Research*, **55** (8), 6392–6416. https://doi.org/10.1029/2018wr024604

129. Clifton, C.F., K.T. Day, C.H. Luce, G.E. Grant, M. Safeeq, J.E. Halofsky, and B.P. Staab, 2018: Effects of climate change on hydrology and water resources in the Blue Mountains, Oregon, USA. *Climate Services*, **10**, 9–19. https://doi.org/10.1016/j.cliser.2018.03.001

130. Hamlet, A.F., M.M. Elsner, G.S. Mauger, S.-Y. Lee, I. Tohver, and R.A. Norheim, 2013: An overview of the Columbia Basin climate change scenarios project: Approach, methods, and summary of key results. *Atmosphere-Ocean*, **51** (4), 392–415. https://doi.org/10.1080/07055900.2013.819555

131. Ren, J., J.C. Adam, J.A. Hicke, E.J. Hanan, C.L. Tague, M. Liu, C.A. Kolden, and J.T. Abatzoglou, 2021: How does water yield respond to mountain pine beetle infestation in a semiarid forest? *Hydrology and Earth System Sciences*, **25** (9), 4681–4699. https://doi.org/10.5194/hess-25-4681-2021

132. Rust, A.J., S. Saxe, J. McCray, C.C. Rhoades, and T.S. Hogue, 2019: Evaluating the factors responsible for post-fire water quality response in forests of the western USA. *International Journal of Wildland Fire*, **28** (10), 769–784. https://doi.org/10.1071/wf18191

133. Sankey, J.B., J. Kreitler, T.J. Hawbaker, J.L. McVay, M.E. Miller, E.R. Mueller, N.M. Vaillant, S.E. Lowe, and T.T. Sankey, 2017: Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophysical Research Letters*, **44** (17), 8884–8892. https://doi.org/10.1002/2017gl073979

134. Rust, A.J., T.S. Hogue, S. Saxe, and J. McCray, 2018: Post-fire water-quality response in the western United States. *International Journal of Wildland Fire*, **27** (3), 203–216. https://doi.org/10.1071/wf17115

135. Pennino, M.J., S.G. Leibowitz, J.E. Compton, M.T. Beyene, and S.D. LeDuc, 2022: Wildfires can increase regulated nitrate, arsenic, and disinfection byproduct violations and concentrations in public drinking water supplies. *Science of The Total Environment*, **804** (15), 149890. https://doi.org/10.1016/j.scitotenv.2021.149890

136. Rumsey, C.A., M.P. Miller, and G.A. Sexstone, 2020: Relating hydroclimatic change to streamflow, baseflow, and hydrologic partitioning in the Upper Rio Grande Basin, 1980 to 2015. *Journal of Hydrology*, **584**, 124715. https://doi.org/10.1016/j.jhydrol.2020.124715

137. Crozier, L.G., J.E. Siegel, L.E. Wiesebron, E.M. Trujillo, B.J. Burke, B.P. Sandford, and D.L. Widener, 2020: Snake River sockeye and Chinook salmon in a changing climate: Implications for upstream migration survival during recent extreme and future climates. *PLoS ONE*, **15** (9), e0238886. https://doi.org/10.1371/journal.pone.0238886

138. McDonnell, T.C., M.R. Sloat, T.J. Sullivan, C.A. Dolloff, P.F. Hessburg, N.A. Povak, W.A. Jackson, and C. Sams, 2015: Downstream warming and headwater acidity may diminish coldwater habitat in southern Appalachian mountain streams. *PLoS ONE*, **10** (8), e0134757. https://doi.org/10.1371/journal.pone.0134757

139. Ruhí, A., J.D. Olden, and J.L. Sabo, 2016: Declining streamflow induces collapse and replacement of native fish in the American Southwest. *Frontiers in Ecology and the Environment*, **14** (9), 465–472. https://doi.org/10.1002/fee.1424

140. Littell, J.S., S.A. McAfee, and G.D. Hayward, 2018: Alaska snowpack response to climate change: Statewide snowfall equivalent and snowpack water scenarios. *Water*, **10** (5), 668. https://doi.org/10.3390/w10050668

141. Littell, J.S., J.H. Reynolds, K.K. Bartz, S.A. McAfee, and G. Hayward, 2020: So goes the snow: Alaska snowpack changes and impacts on Pacific salmon in a warming climate (U.S. National Park Service). *Alaska Park Science*, **19** (1), 62–75. https://www.nps.gov/articles/aps-19-1-10.htm

142. Nash, C.S., G.E. Grant, S. Charnley, j.B. Dunham, H. Gosnell, M.B. Hausner, D.S. Pilliod, and J.D. Taylor, 2021: Great expectations: Deconstructing the process pathways underlying beaver-related restoration. *BioScience*, **71** (3), 249–267. https://doi.org/10.1093/biosci/biaa165

143. Stevenson, J.R., J.B. Dunham, S.M. Wondzell, and J. Taylor, 2022: Dammed water quality—Longitudinal stream responses below beaver ponds in the Umpqua River Basin, Oregon. *Ecohydrology*, **15** (4), e2430. https://doi.org/10.1002/eco.2430

144. Wondzell, S.M., M. Diabat, and R. Haggerty, 2019: What matters most: Are future stream temperatures more sensitive to changing air temperatures, discharge, or riparian vegetation? *JAWRA Journal of the American Water Resources Association*, **55** (1), 116–132. https://doi.org/10.1111/1752-1688.12707

145. Stephens, S.L., J.D. McIver, R.E. Boerner, C.J. Fettig, J.B. Fontaine, B.R. Hartsough, P.L. Kennedy, and D.W. Schwilk, 2012: The effects of forest fuel-reduction treatments in the United States. *BioScience*, **62** (6), 549–560. https://doi.org/10.1525/bio.2012.62.6.6

146. Stephens, S.L., A.L. Westerling, M.D. Hurteau, M.Z. Peery, C.A. Schultz, and S. Thompson, 2020: Fire and climate change: Conserving seasonally dry forests is still possible. *Frontiers in Ecology and the Environment*, **18** (6), 354–360. https://doi.org/10.1002/fee.2218

147. Peterson, D.L. and J.E. Halofsky, 2018: Adapting to the effects of climate change on natural resources in the Blue Mountains, USA. *Climate Services*, **10**, 63–71. https://doi.org/10.1016/j.cliser.2017.06.005

148. Halofsky, J., D. Peterson, K. Metlen, M. Myer, and V. Sample, 2016: Developing and implementing climate change adaptation options in forest ecosystems: A case study in southwestern Oregon, USA. *Forests*, **7** (11), 268. https://doi.org/10.3390/f7110268

149. Timberlake, T.J. and C.A. Schultz, 2019: Climate change vulnerability assessment for forest management: The case of the U.S. Forest Service. *Forests*, **10** (11), 1030. https://doi.org/10.3390/f10111030

150. Ontl, T.A., C. Swanston, L.A. Brandt, P.R. Butler, A.W. D'Amato, S.D. Handler, M.K. Janowiak, and P.D. Shannon, 2018: Adaptation pathways: Ecoregion and land ownership influences on climate adaptation decision-making in forest management. *Climatic Change*, **146** (1), 75–88. https://doi.org/10.1007/s10584-017-1983-3

151. PADEP, 2021: Pennsylvania Climate Action Plan 2021. Pennsylvania Department of Environmental Protection, Harrisburg, PA. https://www.dep.pa.gov/citizens/climate/pages/pa-climate-action-plan.aspx

152. Fischer, A.P., 2019: Adapting and coping with climate change in temperate forests. *Global Environmental Change*, **54**, 160–171. https://doi.org/10.1016/j.gloenvcha.2018.10.011

153. ITEP, 2021: Tribal Climate Change Assessments and Adaptation Plans. Institute for Tribal Environmental Professionals, 10 pp. http://www7.nau.edu/itep/main/tcc/docs/resources/9_tribalccassessmentsadaptationplans_08_27_21.pdf

154. Adaptation Partners, 2023: The Climate Change Adaptation Library for the Western United States. Adaptation Partners. http://adaptationpartners.org/library.php

155. Schuurman, G.W., C.H. Hoffman, D.N. Cole, D.J. Lawrence, J.M. Morton, D.R. Magness, A.E. Cravens, S. Covington, R. O'Malley, and N.A. Fisichelli, 2020: Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager. Natural Resource Report. NPS/NRSS/CCRP/NRR—2020/2213. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://doi.org/10.36967/nrr-2283597

156. Sass, E.M., B.J. Butler, and M. Markowski-Lindsay, 2020: Distribution of Forest Ownerships across the Conterminous United States, 2017. Res. Map NRS-11. U.S. Department of Agriculture, Forest Service, Northern Research Station, Madison, WI. https://doi.org/10.2737/nrs-rmap-11

157. Long, J.W., F.K. Lake, and R.W. Goode, 2021: The importance of Indigenous cultural burning in forested regions of the Pacific West, USA. *Forest Ecology and Management*, **500**, 119597. https://doi.org/10.1016/j.foreco.2021.119597

158. Marks-Block, T., F.K. Lake, and L.M. Curran, 2019: Effects of understory fire management treatments on California hazelnut, an ecocultural resource of the Karuk and Yurok Indians in the Pacific Northwest. *Forest Ecology and Management*, **450**, 117517. https://doi.org/10.1016/j.foreco.2019.117517

159. WA DNR, 2020: 20-Year Forest Health Strategic Plan: Eastern Washington. Washington Department of Natural Resources. https://www.dnr.wa.gov/publications/rp_forest_health_20_year_strategic_plan.pdf

160. St.Clair, J.B., B.A. Richardson, N. Stevenson-Molnar, G.T. Howe, A.D. Bower, V.J. Erickson, B. Ward, D. Bachelet, F.F. Kilkenny, and T. Wang, 2022: Seedlot selection tool and climate-smart restoration tool: Web-based tools for sourcing seed adapted to future climates. *Ecosphere*, **13** (5), e4089. https://doi.org/10.1002/ecs2.4089

161. NIACS, 2022: The Nature Conservancy: Restoring and Connecting Forests in Cuyahoga Valley National Park. Northern Institute of Applied Climate Science. https://forestadaptation.org/adapt/demonstration-projects/nature-conservancy-restoring-and-connecting-forests-cuyahoga-valley

162. NIACS, 2022: The Nature Conservancy: Setting Northern New York Forests on Climate-Adapted Trajectories by Improving Regeneration & Forest Structure. Northern Institute of Applied Climate Science. https://forestadaptation.org/adapt/demonstration-projects/nature-conservancy-setting-northern-new-york-forests-climate-adapted

163. Piana, M.R., C.C. Pregitzer, and R.A. Hallett, 2021: Advancing management of urban forested natural areas: Toward an urban silviculture? *Frontiers in Ecology and the Environment*, **19** (9), 526–535. https://doi.org/10.1002/fee.2389

164. Piana, M.R., R.A. Hallett, M.L. Johnson, N.F. Sonti, L.A. Brandt, M.F.J. Aronson, M. Ashton, M. Blaustein, D. Bloniarz, A.A. Bowers, M.E. Carr, V. D'Amico, L. Dewald, H. Dionne, D.A. Doroski, R.T. Fahey, H. Forgione, T. Forrest, J. Hale, E. Hansen, L. Hayden, S. Hines, J.M. Hoch, T. Ieataka, S.B. Lerman, C. Murphy, E. Nagele, K. Nislow, D. Parker, C.C. Pregitzer, L. Rhodes, J. Schuler, A. Sherman, T. Trammell, B.M. Wienke, T. Witmer, T. Worthley, and I. Yesilonis, 2021: Climate adaptive silviculture for the city: Practitioners and researchers co-create a framework for studying urban oak-dominated mixed hardwood forests. *Frontiers in Ecology and Evolution*, **9**, 750495. https://doi.org/10.3389/fevo.2021.750495

165. Pregitzer, C.C., S. Charlop-Powers, S. Bibbo, H.M. Forgione, B. Gunther, R.A. Hallett, and M.A. Bradford, 2019: A city-scale assessment reveals that native forest types and overstory species dominate New York City forests. *Ecological Applications*, **29** (1), e01819. https://doi.org/10.1002/eap.1819

166. Tribal Adaptation Menu Team, 2019: Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu. Great Lakes Indian Fish and Wildlife Commission, Odanah, WI, 54 pp. https://forestadaptation.org/tribal-climate-adaptation-menu

167. NIACS, 2022: Mark Twain National Forest: Red Bluff Recreation Area. Northern Institute of Applied Climate Science. https://forestadaptation.org/adapt/demonstration-projects/mark-twain-national-forest-red-bluff-recreation-area

168. Álvarez-Berríos, N.L., S.S. Wiener, K.A. McGinley, A.B. Lindsey, and W.A. Gould, 2021: Hurricane effects, mitigation, and preparedness in the Caribbean: Perspectives on high importance–low prevalence practices from agricultural advisors. *Journal of Emergency Management*, **19** (8), 135–155. https://doi.org/10.5055/jem.0585

169. Wiener, S.S., N.L. Álvarez-Berríos, and A.B. Lindsey, 2020: Opportunities and challenges for hurricane resilience on agricultural and forest land in the U.S. Southeast and Caribbean. *Sustainability*, **12** (4), 1364. https://doi.org/10.3390/su12041364

170. Knapp, E.E., A.A. Bernal, J.M. Kane, C.J. Fettig, and M.P. North, 2021: Variable thinning and prescribed fire influence tree mortality and growth during and after a severe drought. *Forest Ecology and Management*, **479**, 118595. https://doi.org/10.1016/j.foreco.2020.118595

171. McCauley, L.A., J.B. Bradford, M.D. Robles, R.K. Shriver, T.J. Woolley, and C.A. Andrews, 2022: Landscape-scale forest restoration decreases vulnerability to drought mortality under climate change in southwest USA ponderosa forest. *Forest Ecology and Management*, **509**, 120088. https://doi.org/10.1016/j.foreco.2022.120088

172. Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Povak, and F.K. Lake, 2021: Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*, **31** (8), e02432. https://doi.org/10.1002/eap.2432

173. Lake, F.K., 2021: Indigenous fire stewardship: Federal/Tribal partnerships for wildland fire research and management. *Fire Management Today*, **79** (1), 30–39. https://www.fs.usda.gov/treesearch/pubs/62060

174. Messier, C., J. Bauhus, F. Doyon, F. Maure, R. Sousa-Silva, P. Nolet, M. Mina, N. Aquilué, M.-J. Fortin, and K. Puettmann, 2019: The functional complex network approach to foster forest resilience to global changes. *Forest Ecosystems*, **6** (1), 21. https://doi.org/10.1186/s40663-019-0166-2

175. Grossiord, C., 2020: Having the right neighbors: How tree species diversity modulates drought impacts on forests. *New Phytologist*, **228** (1), 42–49. https://doi.org/10.1111/nph.15667

176. Berrouet, L.M., J. Machado, and C. Villegas-Palacio, 2018: Vulnerability of socio-ecological systems: A conceptual Framework. *Ecological Indicators*, **84**, 632–647. https://doi.org/10.1016/j.ecolind.2017.07.051

177. Olander, L., K. Warnell, T. Warziniack, Z. Ghali, C. Miller, and C. Neelan, 2021: Exploring the use of ecosystem services conceptual models to account for the benefits of public lands: An example from national forest planning in the United States. *Forests*, **12** (3), 267. https://doi.org/10.3390/f12030267

178. Schelhas, J., S. Hitchner, C. Johnson Gaither, R. Fraser, V. Jennings, and A. Diop, 2017: Engaging African American landowners in sustainable forest management. *Journal of Forestry*, **115** (1), 26–33. https://doi.org/10.5849/jof.15-116

179. Kramer, A.L., J. Liu, L. Li, R. Connolly, M. Barbato, and Y. Zhu, 2023: Environmental justice analysis of wildfire-related $PM_{2.5}$ exposure using low-cost sensors in California. *Science of The Total Environment*, **856**, 159218. https://doi.org/10.1016/j.scitotenv.2022.159218

180. Thomas, A., J. Sánchez, and D. Flores, 2022: A review of trends and knowledge gaps in Latinx outdoor recreation on federal and state public lands. *Journal of Park and Recreation Administration*, **40** (1). https://doi.org/10.18666/jpra-2021-11064

181. Baumflek, M., K.-A. Kassam, C. Ginger, and M.R. Emery, 2021: Incorporating biocultural approaches in forest management: Insights from a case study of Indigenous plant stewardship in Maine, USA and New Brunswick, Canada. *Society & Natural Resources*, **34** (9), 1155–1173. https://doi.org/10.1080/08941920.2021.1944411

182. Dockry, M.J. and S.J. Hoagland, 2017: A special issue of the *Journal of Forestry*—Tribal forest management: Innovations for sustainable forest management. *Journal of Forestry*, **115** (5), 339–340. https://doi.org/10.5849/jof-2017-040

183. Yazzie, J.O., P.Z. Fulé, Y.-S. Kim, and A. Sánchez Meador, 2019: Diné kinship as a framework for conserving native tree species in climate change. *Ecological Applications*, **29** (6), e01944. https://doi.org/10.1002/eap.1944

184. Sáenz-Romero, C., G. Neill, S.N. Aitken, and R. Lindig-Cisneros, 2021: Assisted migration field tests in Canada and Mexico: Lessons, limitations, and challenges. *Forests*, **12** (1), 9. https://doi.org/10.3390/f12010009

185. Leech, S.M., P.L. Almuedo, and G. O'Neill, 2011: Assisted migration: Adapting forest management to a changing climate. *Journal of Ecosystems and Management*, **12** (3). https://doi.org/10.22230/jem.2011v12n3a91

186. Pérez, I., J.D. Anadón, M. Díaz, G.G. Nicola, J.L. Tella, and A. Giménez, 2012: What is wrong with current translocations? A review and a decision-making proposal. *Frontiers in Ecology and the Environment*, **10** (9), 494–501. https://doi.org/10.1890/110175

187. Karasov-Olson, A., M.W. Schwartz, J.D. Olden, S. Skikne, J.J. Hellman, S. Allen, C. Brigham, D. Buttke, D.J. Lawrence, A.J. Miller-Rushing, J.T. Morisette, G.W. Schuurman, M. Trammell, and C. Hawkins-Hoffma, 2021: Ecological Risk Assessment of Managed Relocation as a Climate Change Adaptation Strategy. Natural Resource Report. NPS/NRSS/CCRP/NRR—2021/2241. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://doi.org/10.36967/nrr-2284919.

188. Fargione, J., D.L. Haase, O.T. Burney, O.A. Kildisheva, G. Edge, S.C. Cook-Patton, T. Chapman, A. Rempel, M.D. Hurteau, K.T. Davis, S. Dobrowski, S. Enebak, R. De La Torre, A.A.R. Bhuta, F. Cubbage, B. Kittler, D. Zhang, and R.W. Guldin, 2021: Challenges to the reforestation pipeline in the United States. *Frontiers in Forests and Global Change*, **4**, 629198. https://doi.org/10.3389/ffgc.2021.629198

189. Chambwera, M., G. Heal, C. Dubeux, S. Hallegatte, L. Leclerc, A. Markandya, B.A. McCarl, R. Mechler, and J.E. Neumann, 2014: Ch. 17. Economics of adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 945–977. https://www.ipcc.ch/report/ar5/wg2/

190. UNECE, 2021: Forest Sector Outlook Study, 2020–2040. ECE/TIM/SP/51. United Nations Economic Commission for Europe and the Food and Agriculture Organization of the United Nations, Geneva, Switzerland, 103 pp. https://unece.org/sites/default/files/2022-05/unece-fao-sp-51-main-report-forest-sector-outlook_0.pdf

191. Andersson, E. and E.C.H. Keskitalo, 2018: Adaptation to climate change? Why business-as-usual remains the logical choice in Swedish forestry. *Global Environmental Change*, **48**, 76–85. https://doi.org/10.1016/j.gloenvcha.2017.11.004

192. Anderson, S., T.L. Anderson, A.C. Hill, M.E. Kahn, H. Kunreuther, G.D. Libecap, H. Mantripragada, P. Mérel, A.J. Plantinga, V. Kerry Smith, 2019: The critical role of markets in climate change adaptation. *Climate Change Economics*, **10** (1), 1950003. https://doi.org/10.1142/s2010007819500039

193. Nordhaus, W., 2019: Climate change: The ultimate challenge for economics. *American Economic Review*, **109** (6), 1991–2014. https://doi.org/10.1257/aer.109.6.1991

194. Hashida, Y., J. Withey, D.J. Lewis, T. Newman, and J.D. Kline, 2020: Anticipating changes in wildlife habitat induced by private forest owners' adaptation to climate change and carbon policy. *PLoS ONE*, **15** (4), e0230525. https://doi.org/10.1371/journal.pone.0230525

195. Amacher, G., A.S. Malik, and R.G. Haight, 2006: Reducing social losses from forest fires. *Land Economics*, **82** (3), 367–383. https://doi.org/10.3368/le.82.3.367

196. Scarlett, L. and M. McKinney, 2016: Connecting people and places: The emerging role of network governance in large landscape conservation. *Frontiers in Ecology and the Environment*, **14** (3), 116–125. https://doi.org/10.1002/fee.1247

197. Wyborn, C., A. Datta, J. Montana, M. Ryan, P. Leith, B. Chaffin, C. Miller, and L. van Kerkhoff, 2019: Co-producing sustainability: Reordering the governance of science, policy, and practice. *Annual Review of Environment and Resources*, **44** (1), 319–346. https://doi.org/10.1146/annurev-environ-101718-033103

198. Coop, J.D., S.A. Parks, C.S. Stevens-Rumann, S.D. Crausbay, P.E. Higuera, M.D. Hurteau, A. Tepley, E. Whitman, T. Assal, B.M. Collins, K.T. Davis, S. Dobrowski, D.A. Falk, P.J. Fornwalt, P.Z. Fulé, B.J. Harvey, V.R. Kane, C.E. Littlefield, E.Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K.C. Rodman, 2020: Wildfire-driven forest conversion in western North American landscapes. *BioScience*, **70** (8), 659–673. https://doi.org/10.1093/biosci/biaa061

199. Guiterman, C.H., R.M. Gregg, L.A.E. Marshall, J.J. Beckmann, P.J. van Mantgem, D.A. Falk, J.E. Keeley, A.C. Caprio, J.D. Coop, P.J. Fornwalt, C. Haffey, R.K. Hagmann, S.T. Jackson, A.M. Lynch, E.Q. Margolis, C. Marks, M.D. Meyer, H. Safford, A.D. Syphard, A. Taylor, C. Wilcox, D. Carril, C.A.F. Enquist, D. Huffman, J. Iniguez, N.A. Molinari, C. Restaino, and J.T. Stevens, 2022: Vegetation type conversion in the US Southwest: Frontline observations and management responses. *Fire Ecology*, **18** (1), 6. https://doi.org/10.1186/s42408-022-00131-w

200. Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling, 2009: Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications*, **19** (4), 1003–1021. https://doi.org/10.1890/07-1183.1

201. Abatzoglou, J.T. and C.A. Kolden, 2013: Relationships between climate and macroscale area burned in the western United States. *International Journal of Wildland Fire*, **22** (7), 1003–1020. https://doi.org/10.1071/wf13019

202. Barbero, R., J. Abatzoglou, N. Larkin, C. Kolden, and B. Stocks, 2015: Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire*, **24** (7), 892–899. https://doi.org/10.1071/wf15083

203. Kitzberger, T., D.A. Falk, A.L. Westerling, and T.W. Swetnam, 2017: Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. *PLoS ONE*, **12** (12), e0188486. https://doi.org/10.1371/journal.pone.0188486

204. Fettig, C.J., 2019: Socioecological impacts of the western pine beetle outbreak in Southern California: Lessons for the future. *Journal of Forestry*, **117** (2), 138–143. https://doi.org/10.1093/jofore/fvy029

205. Berner, L.T. and S.J. Goetz, 2022: Satellite observations document trends consistent with a boreal forest biome shift. *Global Change Biology*, **28** (10), 3275–3292. https://doi.org/10.1111/gcb.16121

206. Nigro, K.M., M.E. Rocca, M.A. Battaglia, J.D. Coop, and M.D. Redmond, 2022: Wildfire catalyzes upward range expansion of trembling aspen in southern Rocky Mountain beetle-killed forests. *Journal of Biogeography*, **49** (1), 201–214. https://doi.org/10.1111/jbi.14302

207. Sharma, S., R. Andrus, Y. Bergeron, M. Bogdziewicz, D.C. Bragg, D. Brockway, N.L. Cleavitt, B. Courbaud, A.J. Das, M. Dietze, T.J. Fahey, J.F. Franklin, G.S. Gilbert, C.H. Greenberg, Q. Guo, J.H.R. Lambers, I. Ibanez, J.F. Johnstone, C.L. Kilner, J.M.H. Knops, W.D. Koenig, G. Kunstler, J.M. LaMontagne, D. Macias, E. Moran, J.A. Myers, R. Parmenter, I.S. Pearse, R. Poulton-Kamakura, M.D. Redmond, C.D. Reid, K.C. Rodman, C.L. Scher, W.H. Schlesinger, M.A. Steele, N.L. Stephenson, J.J. Swenson, M. Swift, T.T. Veblen, A.V. Whipple, T.G. Whitham, A.P. Wion, C.W. Woodall, R. Zlotin, and J.S. Clark, 2022: North American tree migration paced by climate in the West, lagging in the East. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (3), e2116691118. https://doi.org/10.1073/pnas.2116691118

208. De Frenne, P., J. Lenoir, M. Luoto, B.R. Scheffers, F. Zellweger, J. Aalto, M.B. Ashcroft, D.M. Christiansen, G. Decocq, K. De Pauw, S. Govaert, C. Greiser, E. Gril, A. Hampe, T. Jucker, D.H. Klinges, I.A. Koelemeijer, J.J. Lembrechts, R. Marrec, C. Meeussen, J. Ogée, V. Tyystjärvi, P. Vangansbeke, and K. Hylander, 2021: Forest microclimates and climate change: Importance, drivers and future research agenda. *Global Change Biology*, **27** (11), 2279–2297. https://doi.org/10.1111/gcb.15569

209. Buchholz, R.R., M. Park, H.M. Worden, W. Tang, D.P. Edwards, B. Gaubert, M.N. Deeter, T. Sullivan, M. Ru, M. Chin, R.C. Levy, B. Zheng, and S. Magzamen, 2022: New seasonal pattern of pollution emerges from changing North American wildfires. *Nature Communications*, **13** (1), 2043. https://doi.org/10.1038/s41467-022-29623-8

210. McClure, C.D. and D.A. Jaffe, 2018: US particulate matter air quality improves except in wildfire-prone areas. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (31), 7901–7906. https://doi.org/10.1073/pnas.1804353115

211. NIFC, 2022: Wildfires and Acres. National Interagency Fire Center. https://www.nifc.gov/fire-information/statistics/wildfires

212. Ticktin, T., K. Kindscher, S. Souther, P.C. Weisberg, James L. Hummel, Susan, C. Mitchell, and S. Sanders, 2018: Ch. 3. Ecological dimensions of nontimber forest product harvest. In: *Assessment of Nontimber Forest Products in the United States Under Changing Conditions*. Chamberlain, J.L., M.R. Emery, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 60–81. https://doi.org/10.2737/srs-gtr-232

213. Lake, F.K., M.R. Emery, M.J. Baumflek, K.S. Friday, K. Kamelamela, L. Kruger, N. Grewe, J. Gilbert, and N.J. Reo, 2018: Ch. 4. Cultural dimensions of nontimber products. In: *Assessment of Nontimber Forest Products in the United States Under Changing Conditions*. Chamberlain, J.L., M.R. Emery, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 16. https://www.fs.usda.gov/research/treesearch/57298

214. Weiskopf, S.R., O.E. Ledee, and L.M. Thompson, 2019: Climate change effects on deer and moose in the Midwest. *The Journal of Wildlife Management*, **83** (4), 769–781. https://doi.org/10.1002/jwmg.21649

215. Wünschmann, A., A.G. Armien, E. Butler, M. Schrage, B. Stromberg, J.B. Bender, A.M. Firshman, and M. Carstensen, 2015: Necropsy findings in 62 opportunistically collected free-ranging moose (*Alces alces*) from Minnesota, USA (2003–13). *Journal of Wildlife Diseases*, **51** (1), 157–65. https://doi.org/10.7589/2014-02-037

216. Carstensen, M., E.C. Hildebrand, D. Plattner, M. Dexter, A. Wünschmann, and A. Armien, 2018: Causes of Non-hunting Mortality of Adult Moose in Minnesota, 2013–2017. Minnesota Department of Natural Resources. https://files.dnr.state.mn.us/wildlife/research/studies/moose/moose_findings.pdf

217. DelGuidice, G.D. and J.H. DelGuidice, 2022: 2022 Aerial Moose Survey. Minnesota Department of Natural Resources, 13 pp. https://files.dnr.state.mn.us/wildlife/moose/moosesurvey.pdf?20220524-17

218. Jones, H., P. Pekins, L. Kantar, I. Sidor, D. Ellingwood, A. Lichtenwalner, and M. O'Neal, 2019: Mortality assessment of moose (*Alces alces*) calves during successive years of winter tick (*Dermacentor albipictus*) epizootics in New Hampshire and Maine (USA). *Canadian Journal of Zoology*, **97** (1), 22–30. https://doi.org/10.1139/cjz-2018-0140

219. Smart, L.S., P.J. Taillie, B. Poulter, J. Vukomanovic, K.K. Singh, J.J. Swenson, H. Mitasova, J.W. Smith, and R.K. Meentemeyer, 2020: Aboveground carbon loss associated with the spread of ghost forests as sea levels rise. *Environmental Research Letters*, **15** (10), 104028. https://doi.org/10.1088/1748-9326/aba136

220. Ury, E.A., X. Yang, J.P. Wright, and E.S. Bernhardt, 2021: Rapid deforestation of a coastal landscape driven by sea-level rise and extreme events. *Ecological Applications*, **31** (5), e02339. https://doi.org/10.1002/eap.2339

221. Bowker, J.M. and A. Askew, 2012: Ch. 8. U.S. outdoor recreation participation projections to 2060. In: *Outdoor Recreation Trends and Futures: A technical Document Supporting the Forest Service 2010 Resources Planning Act Assessment*. Cordell, H.K., Ed. U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, 105–124. https://www.fs.usda.gov/research/treesearch/42080

222. Norström, A.V., C. Cvitanovic, M.F. Löf, S. West, C. Wyborn, P. Balvanera, A.T. Bednarek, E.M. Bennett, R. Biggs, A. de Bremond, B.M. Campbell, J.G. Canadell, S.R. Carpenter, C. Folke, E.A. Fulton, O. Gaffney, S. Gelcich, J.-B. Jouffray, M. Leach, M. Le Tissier, B. Martín-López, E. Louder, M.-F. Loutre, A.M. Meadow, H. Nagendra, D. Payne, G.D. Peterson, B. Reyers, R. Scholes, C.I. Speranza, M. Spierenburg, M. Stafford-Smith, M. Tengö, S. van der Hel, I. van Putten, and H. Österblom, 2020: Principles for knowledge co-production in sustainability research. *Nature Sustainability*, **3** (3), 182–190. https://doi.org/10.1038/s41893-019-0448-2

223. Violle, C., M.-L. Navas, D. Vile, E. Kazakou, C. Fortunel, I. Hummel, and E. Garnier, 2007: Let the concept of trait be functional! *Oikos*, **116** (5), 882–892. https://doi.org/10.1111/j.0030-1299.2007.15559.x

224. Pretzsch, H., D.I. Forrester, and J. Bauhus, Eds., 2017: *Mixed-Species Forests: Ecology and Management*. Springer, Heidelberg, Germany. https://doi.org/10.1007/978-3-662-54553-9

225. Vernon, M.J., R.L. Sherriff, P. van Mantgem, and J.M. Kane, 2018: Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California. *Forest Ecology and Management*, **422**, 190–198. https://doi.org/10.1016/j.foreco.2018.03.043

226. Andrews, C.M., A.W. D'Amato, S. Fraver, B. Palik, M.A. Battaglia, and J.B. Bradford, 2020: Low stand density moderates growth declines during hot droughts in semi-arid forests. *Journal of Applied Ecology*, **57** (6), 1089–1102. https://doi.org/10.1111/1365-2664.13615

227. Steckel, M., W.K. Moser, M. del Río, and H. Pretzsch, 2020: Implications of reduced stand density on tree growth and drought susceptibility: A study of three species under varying climate. *Forests*, **11** (6), 627. https://doi.org/10.3390/f11060627

Fifth National Climate Assessment: Chapter 8

# Ecosystems, Ecosystem Services, and Biodiversity

# Chapter 8. Ecosystems, Ecosystem Services, and Biodiversity

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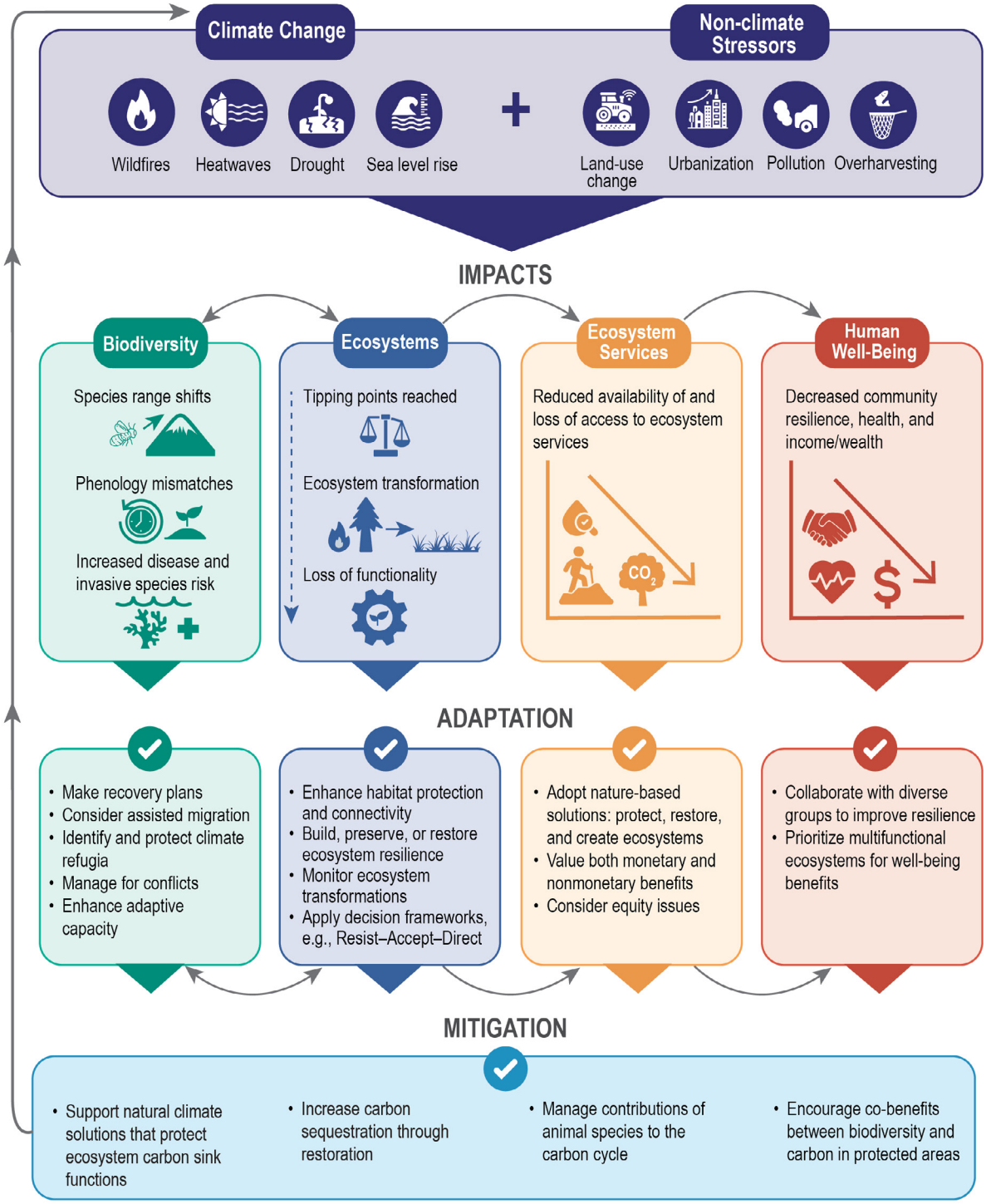
# Introduction

Human well-being is dependent on natural and managed ecosystems, which provide crucial functions and resources for nearly everything we eat, make, and do.[1] Clean water and air, soils and nutrients for food production, timber for construction, and other supplies and services we depend on all come from nature. But many ecosystems are increasingly facing climate risks and impacts that alter ecological processes and functions and affect species across all levels of the food web. These changes in turn can result in reduced biodiversity and diminished ecosystem services (the benefits received from natural systems; Figure 8.1).[2,3] Relationships between humans and ecosystems, such as the kinship values that many Black, Indigenous and Tribal communities experience with regard to nature, are also endangered by these changes.[4,5]

## Climate Change and Ecosystems, Biodiversity, and Ecosystem Services

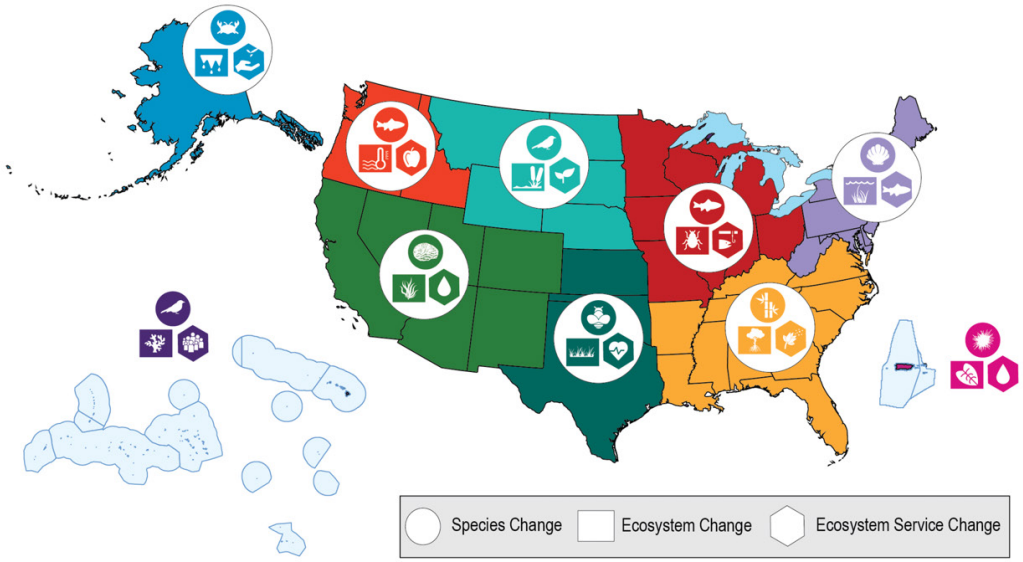



**Climate and non-climate stressors together affect biodiversity, ecosystems, and the services they provide.**

**Figure 8.1.** Species and ecosystems respond to pressures in different ways, such as shifting their locations or transforming into new, often degraded systems less able to provide ecosystem services.[6] Adaptation measures can help species and ecosystems cope with some climate impacts but are not always going to be effective or feasible, requiring increasingly difficult decisions on what resources to prioritize and what changes to accept.[7] Adapted from Lipton et al. 2018.[8]

Climate change impacts are already seen in the deterioration of ecosystem functions, as well as in changes in marine and terrestrial primary productivity (growth of plants and algae) and the balance between primary production and respiration (i.e., carbon balances).[2] Ecosystem degradation increases risks to human populations, such as in coastal areas where loss of wetlands increases damage from storms (KM 9.2). Other observed impacts include range shifts as species expand into new regions or disappear from unfavorable areas, altered timing of seasonal and life-cycle events, increased mortality and localized extinctions, and spread of diseases and invasive species (Figure 8.2).[9,10] These risks are projected to grow with additional degrees of warming (Figure 8.3),[11,12] as well as with increased atmospheric carbon dioxide, which contributes to the acidification of marine ecosystems (KM 10.1).[13]

## Regional Impacts

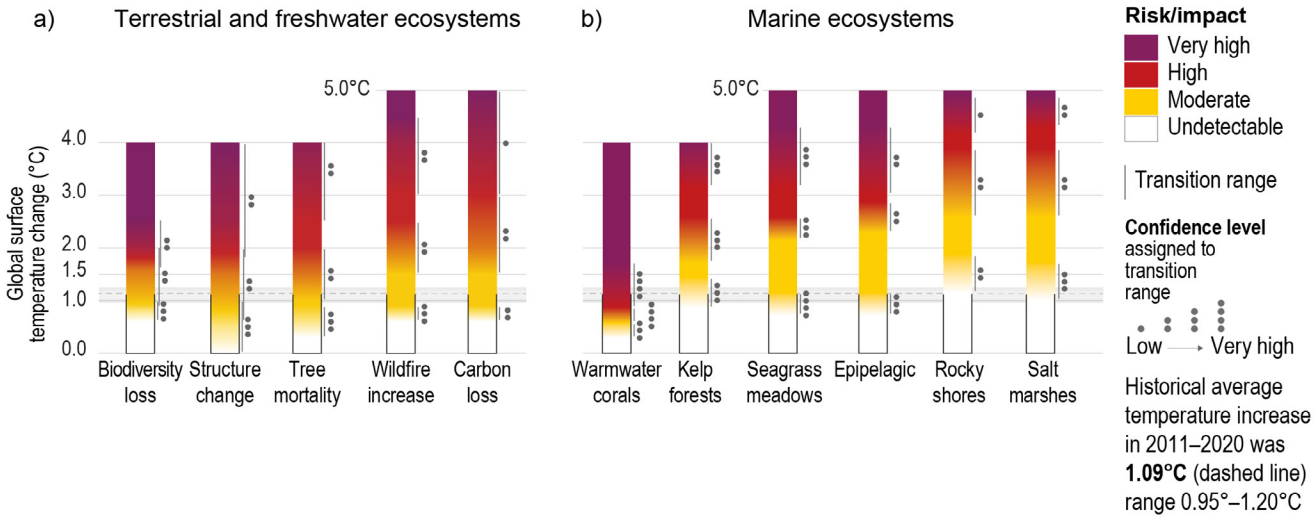



| NCA Region | Species Change | Ecosystem Change | Ecosystem Service Change |
|---|---|---|---|
| Alaska | Commercial crab decline (KM 29.5) | Permafrost thaw and erosion (KM 29.5) | Cultural identity loss (Box 29.3) |
| Northern Great Plains | Grassland bird decline (KM 25.2) | Prairie wetlands threats (Box 25.2) | Delayed harvest of culturally important plants (KM 25.3) |
| Midwest | Brook trout decline (KM 24.2) | Increased agricultural pests (KM 24.1) | Recreational lake ice loss (Figure 24.6) |
| Northeast | Sea scallop decline (KM 21.2) | Coastal habitat loss (KM 21.2) | Impacts to fishing communities (KM 21.2) |
| Southeast | Rivercane loss (Box 22.3) | Coastal forest degradation (KM 22.1) | Increased pollen (KM 22.2) |
| US Caribbean | Sargassum seaweed increase (KM 23.4) | Tropical forest productivity declines (KM 23.2) | Reduction in water availability (KM 23.3) |
| Southern Great Plains | Pollinator disruptions (KM 26.2) | Decreased rangeland health (KM 26.1) | Extreme heat affecting human health (KM 26.3) |
| Southwest | Red abalone critically endangered (KM 28.2) | Kelp forest decline (KM 28.2) | Reduced water availability (KM 28.1) |
| Hawai'i and US-Affiliated Pacific Islands | Avian extinctions (KM 30.4) | Coral reef loss (KM 30.1) | Cultural practices threats (Box 30.6) |
| Northwest | Invasive bass increase (KM 27.2) | Marine heatwaves (KM 27.2) | Reduced crop yields (KM 27.3) |

**All US regions are experiencing impacts of climate change on species, ecosystems, and ecosystem services.**

**Figure 8.2.** Regional examples show the wide range of potential ecosystem impacts and their socioeconomic ramifications. Some changes may be occurring in more than one region (e.g., loss of coral reefs in both Hawai'i and the US-Affiliated Pacific Islands [USAPI] and in the US Caribbean). Figure credit: Rutgers University and USGS.

## Ecosystem Impacts and Risks




**Ecosystem impacts and risks increase at higher levels of global warming.**

**Figure 8.3.** As global surface temperatures increase relative to the preindustrial period (1850–1900), risks to ecosystems, such as changes in structure and function, become more acute beyond the 1.09°C (1.96°F) of warming that has already occurred (light gray dashed line). Maximum risk is reached below 4°C (7.2°F) of warming in some cases and between 4° and 5°C (9°F) in others. Very high risks to sensitive ecosystems, such as coral reefs, are anticipated above 2°C (3.6°F) and will be difficult to reverse. Adapted with permission from Figure SPM.3 in IPCC 2022.[2]

Ecosystem-based and climate-informed management that anticipates and adapts to changes can limit damage and increase resilience of ecosystems (Figure 6.7; KM 6.2).[14] Strategies include restoration, habitat protection and connectivity, assisted migration, and adaptive management.[15,16] However, there are limits to adaptive management, particularly for unique systems and species and the humans who depend on them.[2] For example, adaptive management may not be able to keep up with rising sea levels that submerge coastal communities and ecosystems (KM 9.1) or extreme heat that is intolerable to humans or other organisms (KM 15.1).

This chapter focuses on risks to terrestrial, freshwater, and marine ecosystems; more details on the following ecosystems can be found as noted: land (Ch. 6), forests (Ch. 7), coasts (Ch. 9), oceans (Ch. 10), and agroecosystems (Ch. 11).

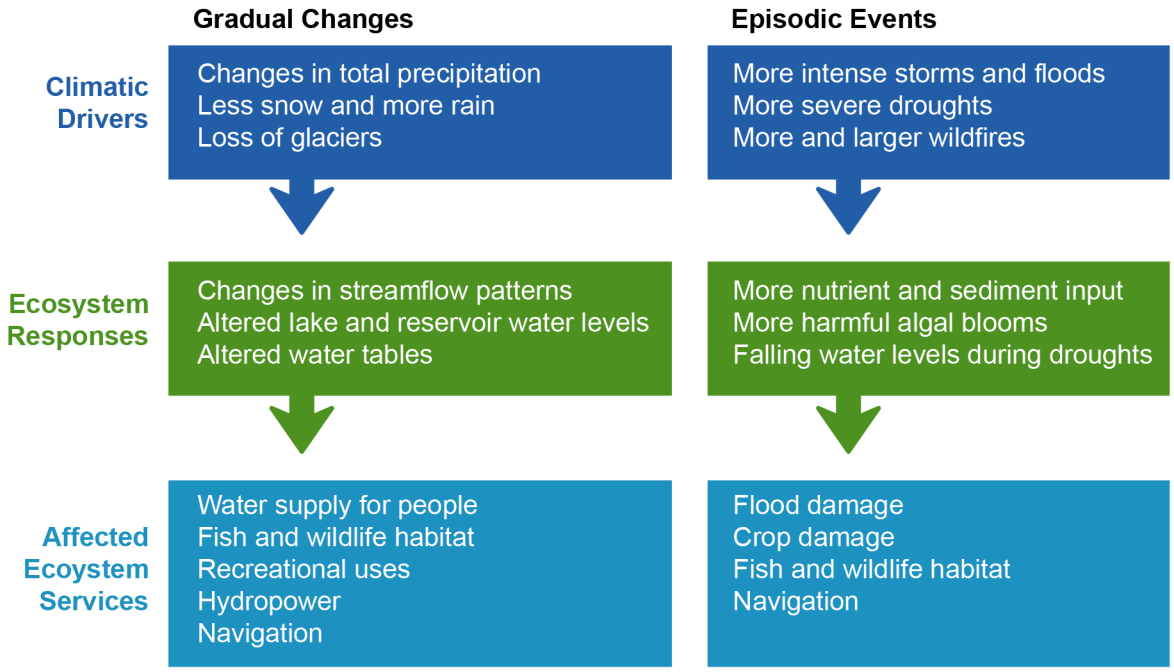
## Key Message 8.1

## Change Is Driving Rapid Ecosystem Transformations

Climate change, together with other stressors, is driving transformational changes in ecosystems, including loss and conversion to other states, and changes in productivity (*very likely*, *high confidence*). These changes have serious implications for human well-being (*very likely*, *high confidence*). Many types of extreme events are increasing in frequency and/or severity and can trigger abrupt ecosystem changes (*medium confidence*). Adaptive governance frameworks, including adaptive management, combined with monitoring can help to prepare for, respond to, and alleviate climate change impacts, as well as build resilience for the future (*medium confidence*).

Ecosystem changes can be driven by physical factors (e.g., thermal stress), biological responses (e.g., changing ranges), or both, often interacting with stressors from human activities. Multiple stressors, both gradual and episodic, can have complex interactive or amplifying effects on ecosystems (Figure 8.4);[17,18] for example, severe hurricanes can heighten forest vulnerability to drought and/or fire.[19,20]

### Amplifying Climate Change Effects on Watersheds

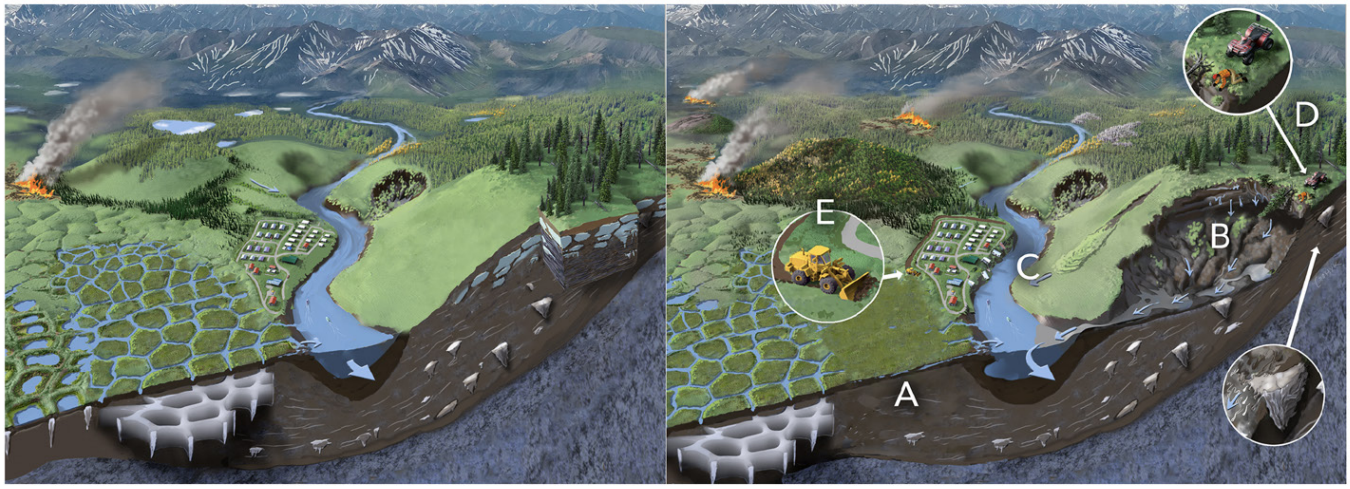



**Climate effects on watersheds exemplify the amplifying impacts of gradual and episodic stressors.**

**Figure 8.4.** Both gradual and episodic (short-lived) climatic drivers alter the transport of water, nutrients, and sediments from terrestrial watersheds to downstream water bodies. These drivers affect aquatic ecology and ecosystem services throughout the hydrological system, even in areas distant from drivers of change (e.g., more intense rainfall leading to leaching of fertilizers that stimulate harmful algal blooms downstream).[21] The frequency and intensity of episodic extreme events is projected to increase (KM 2.2), raising risks for many species (Figure 8.10). Figure credit: Cary Institute of Ecosystem Studies.

Many ecosystems are at increased risk of ecosystem tipping points (where rapid and unpredictable conversions to new states occur),[22] although it is difficult to predict how, where, and when these changes will occur.[23,24] Transformative changes in the composition, structure, function, and other properties of ecosystems result in a new stable state, or regime, with a different combination of species and communities, often resulting in reduced biodiversity and ecosystem services.[25,26] Restoring an ecosystem may be difficult or even impossible if a critical threshold or tipping point is crossed and a different system emerges, because changing or restoring the drivers that led to the altered state may not result in a return to the original state (Figure 8.5).[27]

## Tipping Points and Regime Changes

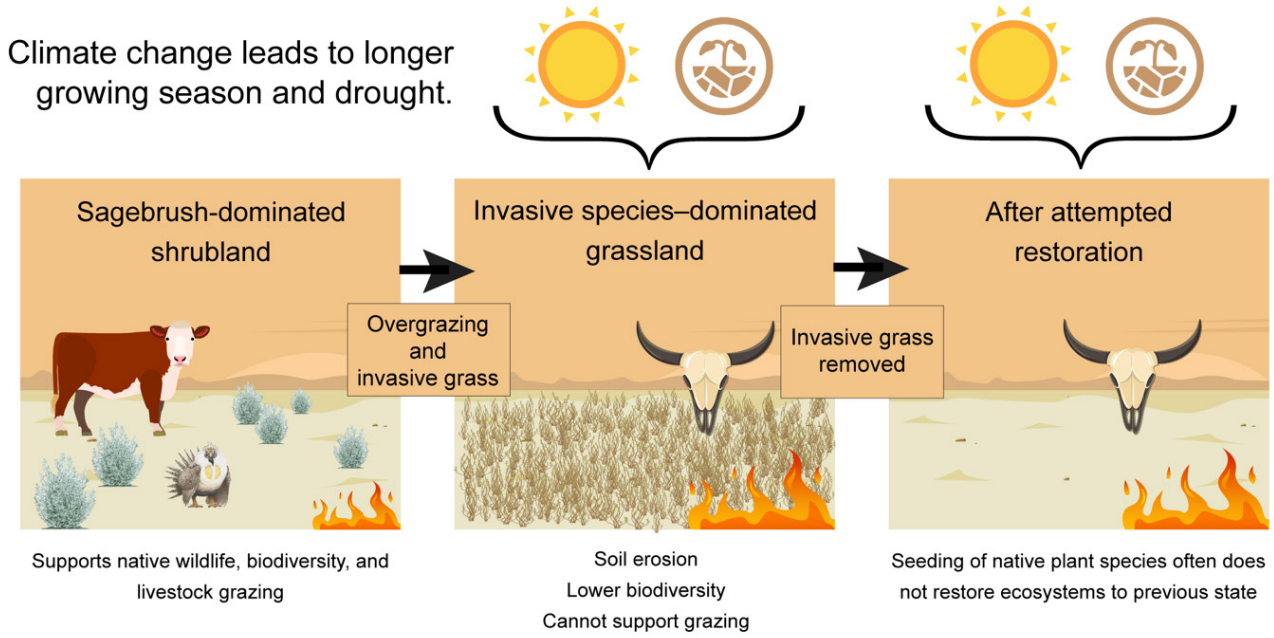



**The Arctic faces substantial impacts from thawing permafrost that cannot be reversed.**

**Figure 8.5.** Thawing of permafrost can cause irreversible tipping points in Arctic landscapes, transforming intact ecosystems (**left**) to severely altered ones (**right**), with impacts on people. A warming climate and fires lead to melting ground ice. Arctic and boreal forests contain permafrost soils with excess ice (more than is contained in soil pores), which form 3D networks in the ground. With warming, this ground ice can melt and the ground surface collapses (**A**). Fires, a natural part of the boreal disturbance cycle, are increasing in extent, frequency, and severity. Melting ice can lead to accumulation of water in ponds, lakes, and wetlands, but continued thawing can cause lakes to drain. Permafrost can also thaw abruptly, causing thaw slumps and bank failures (**B**). These geomorphological changes impact human infrastructure (**C**) and access to the land (**D**). Other risks (not pictured) include chemical and potentially disease mobilization that can threaten human health and ecosystems.[28,29] Human adaptation strategies to permafrost thaw include installing firebreaks around infrastructure (E). Adapted from Schuur et al. 2022[30] [CC BY 4.0].

Ecosystem changes can be gradual or relatively abrupt[31] and depend in part on ecosystem characteristics and key species.[32] Ecosystems with immobile or long-lived species such as corals or trees can often exhibit abrupt responses because they have limited capacity to keep pace.[33,34,35] Ecosystems with higher biodiversity have more species interactions and often exhibit slow changes at first followed by abrupt shifts.[15] Multiple stressors can lead to synergistic effects and trigger abrupt changes.[36] Examples include the co-occurrence of extreme heat, drought, and invasive grasses (Figure 8.6)[22] or wildfires followed by insect infestations (or vice versa; Focus on Western Wildfires).

## Abrupt Changes in Ecosystem State

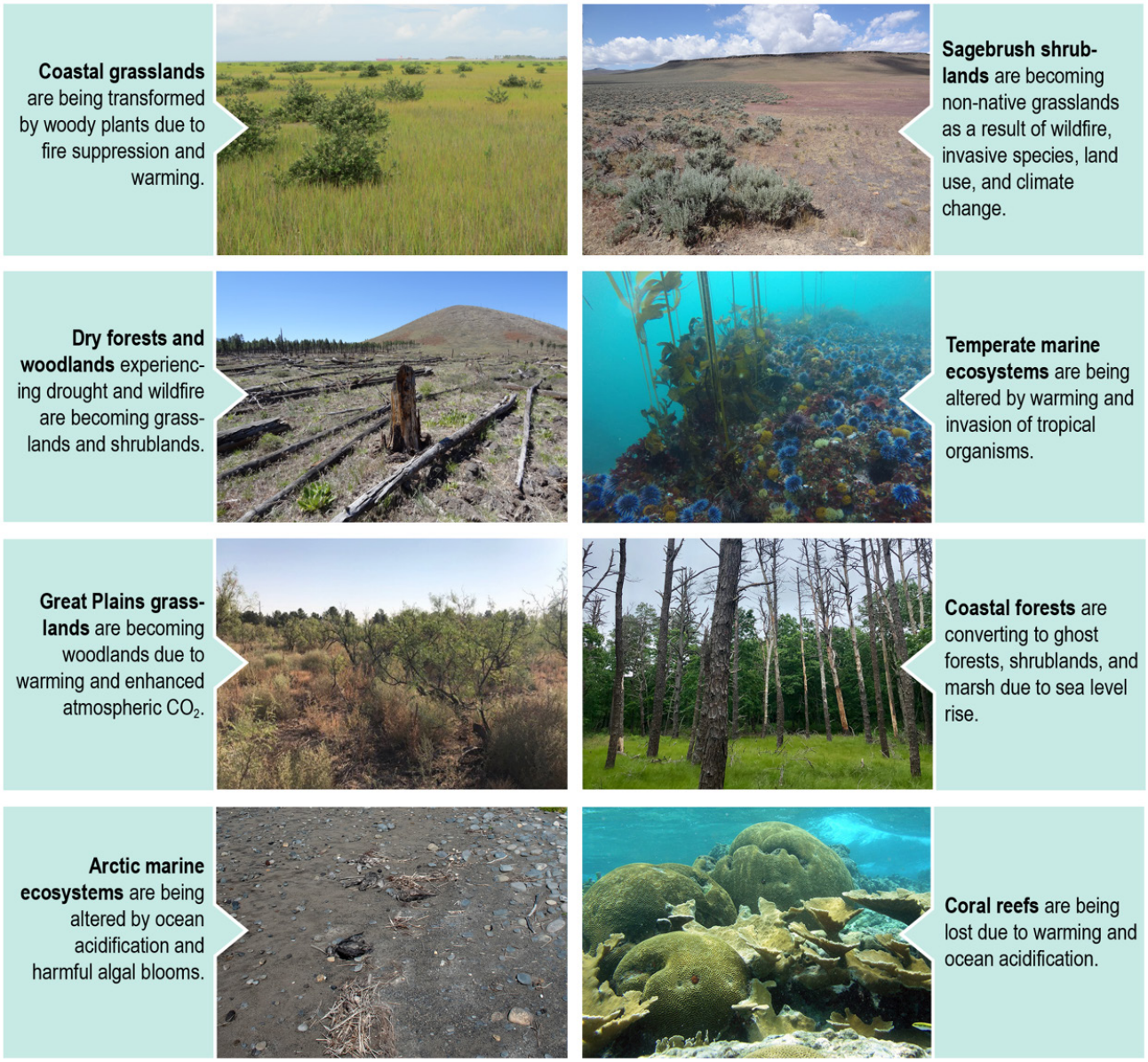



**Climate change interacts with other stressors to cause synergistic effects, and resulting ecosystem changes can be abrupt and difficult to reverse.**

**Figure 8.6.** In the western US, drought and longer, hotter growing seasons combined with invasive grasses and overgrazing have transformed sagebrush shrublands past a tipping point into annual grasslands that experience more frequent wildfires and no longer support native biodiversity and livestock grazing. Removing invasive grasses and seeding with native plants often does not restore the original shrubland ecosystem.[37] Adapted from Foley et al. 2015[38] [CC BY 4.0].

Vulnerability of ecosystems to climate change depends on exposure to the physical drivers of change and characteristics that affect species' sensitivity and capacity to adapt.[39] Examples of vulnerable ecosystems experiencing transformation are increasingly common (Figure 8.7). There is evidence that ecosystems with higher biodiversity are more resilient in the face of climate change,[40,41] indicating that better protection and reduced fragmentation and degradation of ecosystems are potential climate-adaptation strategies.[42]

## Unique and Vulnerable Ecosystems



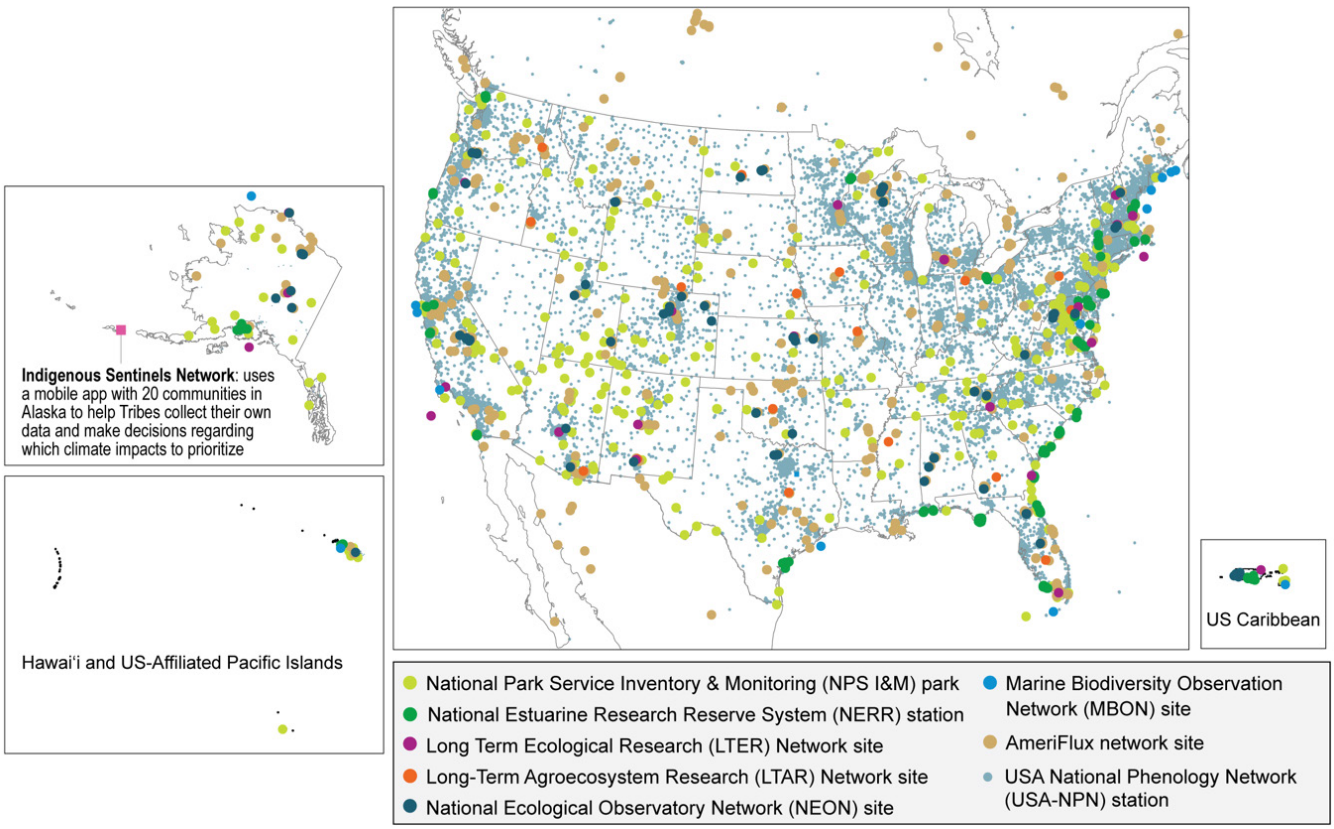

**Transformations to ecosystems are already noticeable and widespread.**

**Figure 8.7.** There are numerous and widespread examples of ecosystems transforming to altered states, with complex drivers and outcomes.[22,43,44,45,46] Climate-driven ecological transformations are occurring in all regions of the US and often negatively impact the services these ecosystems provide, including regulation of carbon and water cycles, wildlife habitat, and recreation. Figure credit: USDA Forest Service, USGS, and NOAA Fisheries. Photo credits (clockwise from top right): John Bradford, USGS; Steve Lonhart/NOAA; ©Elizabeth-Ann Jamison; Ilsa B. Kuffner, USGS; Sarah K. Schoen, USGS; ©Nicholas Smith; John Bradford, USGS; ©Anna Armitage.

## *Monitoring Transformations*

Identifying and monitoring species or ecosystem traits that provide early warnings of vulnerability, system-wide decline, or tipping points can assist in reducing risks.[26,47,48,49] Numerous long-term monitoring networks (Figure 8.8) have been established in recent decades in direct response to climate and other changes.[27,50] Community-led ("citizen") science efforts such as iNaturalist[51] and the USA National Phenology Network,[52] alongside community-based monitoring networks[53] and Indigenous Knowledge holders (KM 16.3)[54] also collect observations across large areas[55] and have helped detect altered species distributions, abundances, and phenologies.[56,57,58]

### Monitoring Ecosystem Changes




**Monitoring programs are critically important for observing and projecting trends in resilience, species invasions, range shifts, declines, and extinctions.**

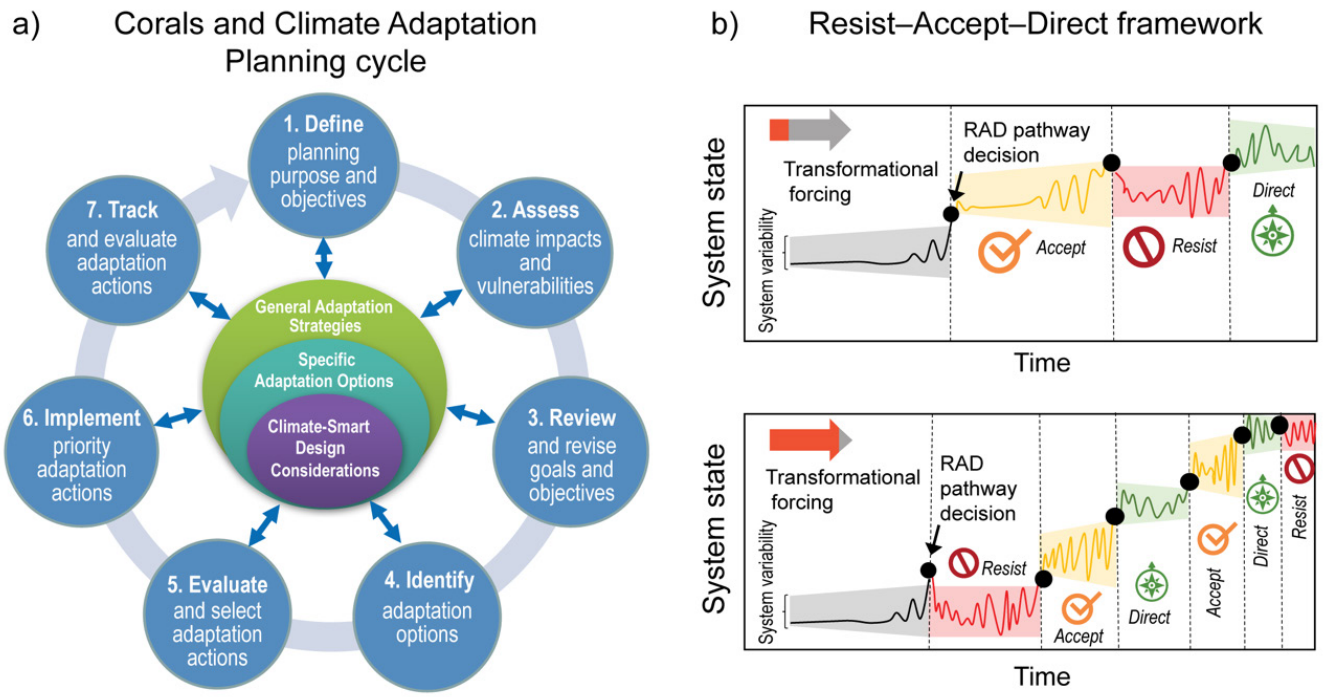
**Figure 8.8.** Federally operated networks (NPS I&M, NERR) and other long-term networks (LTER, LTAR, NEON, MBON, AmeriFlux) provide consistent and permanent observations at limited sites, whereas volunteer networks (USA-NPN, Indigenous Sentinels) offer more opportunistic observations across a wider landscape. Together, these networks provide critical data for understanding species and ecosystem changes, although gaps in coverage remain. Figure credit: Lynker and USGS.

## *Addressing Risks and Managing for Change*

Climate change and other disturbances that transform ecosystems create growing management challenges.[14,59] Building, preserving, or restoring ecosystems is often the most practical and effective resilience strategy;[60,61] however, ecosystem transformation may still be inevitable.[62] Conventional resource management approaches are often ill-suited for managing uncertainties and related trade-offs.[63,64] In contrast, adaptive management iteratively plans, implements, and modifies strategies for managing resources under uncertainty. Successful adaptive management requires an overarching adaptive governance approach that provides institutional structures and decision-making processes for coordinating efforts across scales,[65] managing uncertainties and conflicts,[66,67] mobilizing diverse knowledges, and addressing stakeholder interests.[68,69,70]

Decision frameworks designed to anticipate ecosystem transformation can advance adaptative management processes (Figure 8.9).[71] As one example, the Resist–Accept–Direct (RAD) framework helps identify conditions where ecosystem management can resist a trajectory of change, accept change, or direct change toward desired future conditions (Figure 8.9b).[62,72] To engage the "direct" in their RAD planning, Tetlin National Wildlife Refuge in Alaska is combining scenarios, adaptive management, and adaptive pathway planning to engage managers and stakeholders to explore potential transformations, with one focus specifically on subsistence hunting.[73]

### Adaptation and Transformation Planning Frameworks




**Decision frameworks can help plan for the potential transformation of ecosystems.**

**Figure 8.9.** Two examples of adaptive decision frameworks are the Corals and Climate Adaptation Planning cycle (**a**) and the Resist–Accept–Direct (RAD) framework (**b**). In (a), users are guided through assessment and design considerations to adjust climate-smart management interventions. In (b), the current ecosystem (gray) is affected by either moderate or strong transformational forcing that drives decisions (black dots) to resist (red time periods), accept (yellow time periods), and direct (green time periods) the trajectory of change. (a) Adapted from West et al. 2017, 2018[74,75] [CC BY 4.0]; (b) adapted from Lynch et al. 2022.[72]

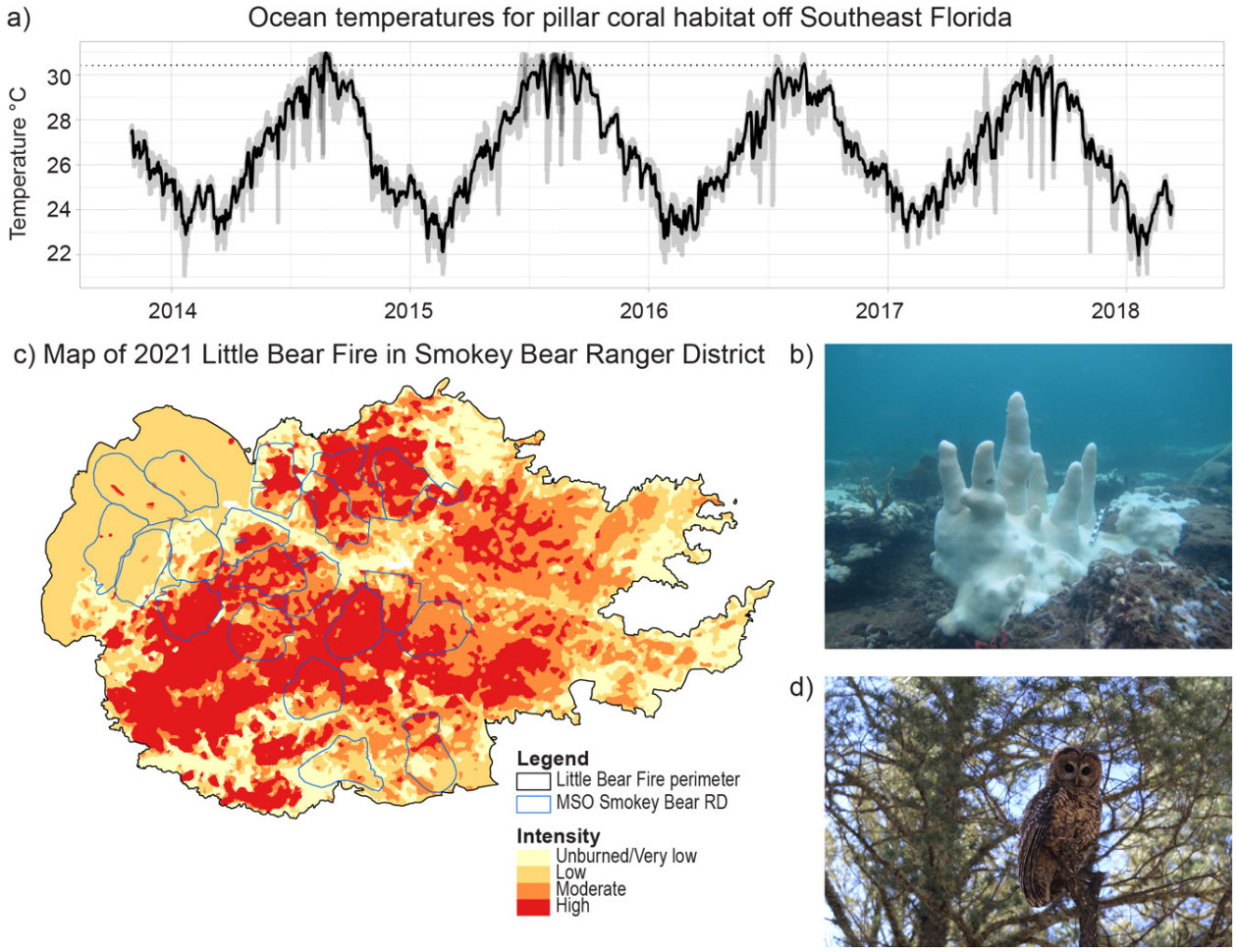
## Key Message 8.2

## Species Changes and Biodiversity Loss Are Accelerating

The interaction of climate change with other stressors is causing biodiversity loss, changes in species distributions and life cycles, and increasing impacts from invasive species and diseases, all of which have economic and social consequences (*very likely*, *high confidence*). Future responses of species and populations will depend on the magnitude and timing of changes, coupled with the differential sensitivity of organisms; species that cannot easily relocate or are highly temperature sensitive may face heightened extinction risks (*very likely*, *high confidence*). Identification of risks (e.g., extreme events) will help prioritize species and locations for protection and improve options for management (*very likely*, *high confidence*).

Climate-related stressors and other drivers of global change, such as land-use change, habitat destruction, and overexploitation, can create significant biodiversity changes and losses (Figure 8.1).[76,77] Even short-term extreme events such as heatwaves[78,79,80] can generate significant species impacts. For example, coral reefs are threatened by cumulative impacts of ocean warming and acidification, marine heatwaves resulting in bleaching and higher susceptibility to diseases, increasingly powerful tropical cyclones causing loss of structural complexity, hypoxia (low oxygen) events, overfishing, and pollution (Figure 8.10a, b; Box 10.1; KMs 9.2, 10.1).[81,82,83,84,85,86] Similarly, wildfires (Focus on Western Wildfires)[87] can create risks for some species both directly (Figure 8.10c, d) and indirectly through longer-term habitat changes.[88]

## Extreme Event Impacts




**Short-term extreme events can have severe impacts on threatened species.**

**Figure 8.10.** Two examples of such impacts are as follows. (**a**) High water temperatures off Southeast Florida exceeded the maximum average monthly temperature (horizonal line in time series) in 2014–2015, resulting in severe bleaching of (**b**) pillar coral (*Dendrogyra cylindrus*) colonies and subsequent disease and death of all individuals. (**c**) Wildfires impacted more than 75% of breeding pairs (blue polygons) of (**d**) Mexican spotted owl (MSO; *Strix occidentalis lucida*) in Smokey Bear Ranger District, New Mexico, in 2012. Figure credits: (a) adapted from Jones et al. 2021[89] [CC BY 4.0]; (c) USDA Forest Service, NOAA Fisheries, and NOAA NCEI. Photo credits: (b) ©David Gilliam, Nova Southeastern University; (d) ©Serra J. Hoagland, USDA Forest Service.

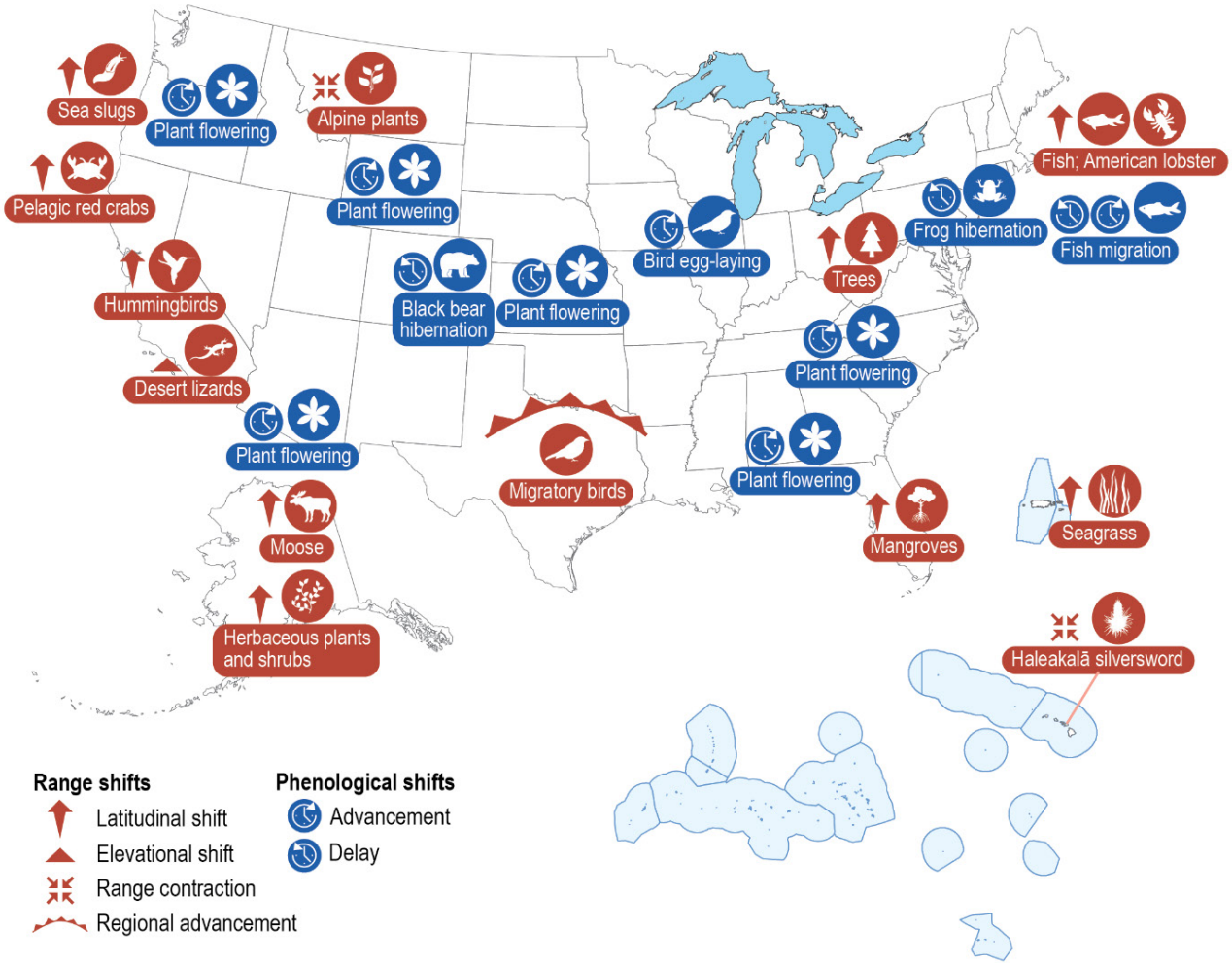
## *Changes in Phenology*

Compounding the responses of species to extreme events, the timing of seasonal events such as leaf-out, flowering, migration, spawning, phytoplankton blooms, and egg hatching is changing in response to rising winter and spring temperatures and to the altered timing and amount of snowmelt and rainfall (Figures 8.8, A4.13).[58,90,91,92] Changes include earlier flowering and maturity in agricultural crops that affect planting and harvest times,[93,94,95,96,97] longer and more intense allergy seasons (KM 14.4),[98] and increased pest activity.[99,100] Changes are most pronounced at high latitudes and elevations and in urbanized areas.[101,102] Phenological mismatches emerge when the timing of activities in interacting species changes at different rates, such as food availability shifting to no longer match a dependent organism's needs.[103,104] Phenological changes are also impacting seasonal carbon cycling[105] and increasing vulnerability to spring frost damage (App. 4).[106] There are significant economic and social impacts of these changes, including tourism impacts and loss of culturally important species.[107,108]

## *Range Shifts*

Elevational and latitudinal range shifts driven by climate change have already occurred for multiple species (Figure 8.11),[109,110,111] with range shifts of marine species more responsive and greater in magnitude than terrestrial ones (KM 10.1; Figure A4.12).[112] Mountaintop ranges are shrinking as species shift upslope, with high-elevation ones highly vulnerable.[113,114] Milder winters and warmer growing seasons are expected to expand ranges for some species.[115,116]

### Observed Range Shifts and Changes in Phenology

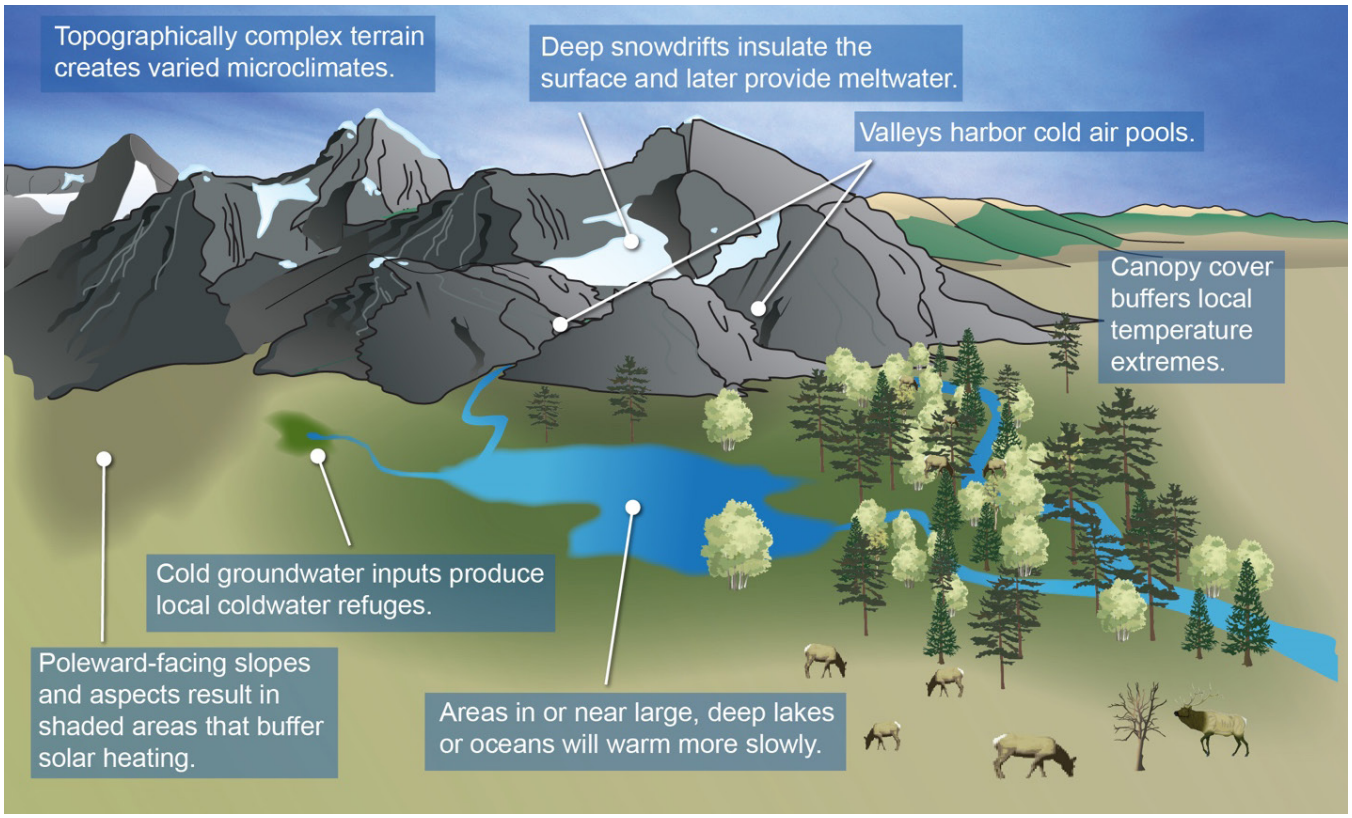



**Climate change is leading to shifts in phenology and range for species across the United States.**

**Figure 8.11.** Many plant and animal species are shifting to higher elevations, to more northern latitudes, or in multiple directions (here labeled "regional advancement"). The timing of seasonal activity is similarly shifting in response to warmer temperatures and changing precipitation regimes, in many cases occurring earlier in the year, although the direction and magnitude of changes are species-specific. Figure credit: University of Arizona and USFWS.

Conditions can change over very localized scales, creating complex "mosaic" patterns of environmental stressors.[117,118,119,120] Climate refugia occur in locations where environmental conditions are changing more slowly than in surrounding areas[121] or where local drivers override more regional-scale processes.[122] These refugia are expected to support organisms that can repopulate other depleted areas through dispersal via currents or land corridors[123] and are therefore a priority for conservation (Figure 8.12).[124,125] Identification of the many existing refugia expected to disappear under climate change is crucial.[126,127]

## Environmental Mosaics and Climate Refugia



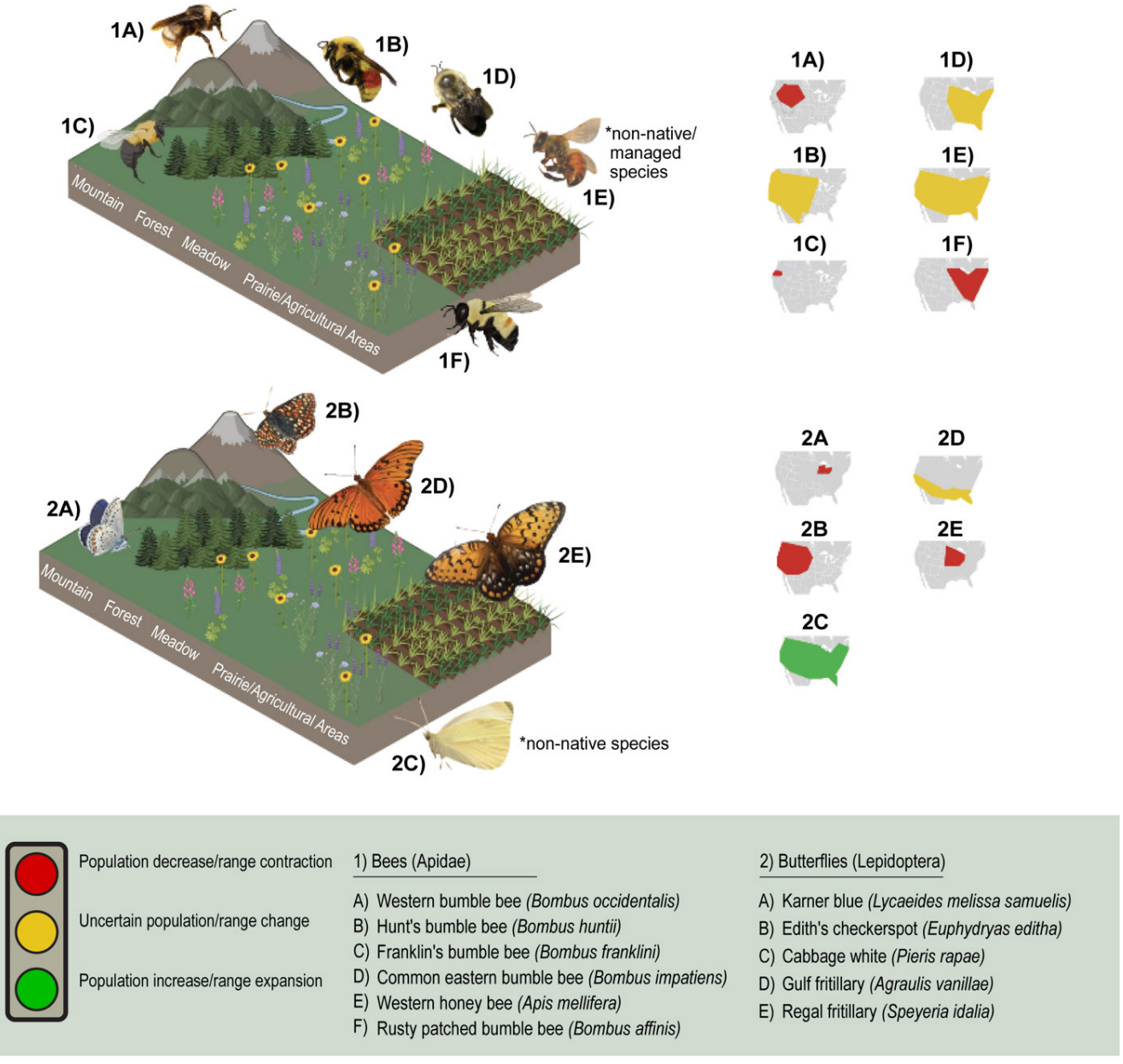

**Climate refugia are locations where environmental conditions are changing more slowly than in the surrounding region.**

**Figure 8.12.** Refugia help populations survive extreme events, and when connected via dispersal currents and corridors can serve as rescue sites.[122] Understanding variations in environmental exposures and organism sensitivities to extreme conditions helps forecast climate impacts[122,127] and inform management strategies.[128,129] Adapted from Morelli et al. 2016[130] [CC0 1.0].

## *Species Sensitivities and Extinction Risks*

Understanding species sensitivities to climate impacts and adaptive capacity can help detect ecological tipping points (KM 8.1).[131,132] Large-bodied animals (Box 8.1)[133] and species occupying polar habitats are particularly at risk of local extinction due to physiological vulnerabilities.[134] In contrast, smaller-bodied species often have more widely variable responses to changing conditions (Figure 8.13).

### Observed Pollinator Sensitivities




**Insect pollinator responses to environmental stressors, even within the same taxonomic grouping, can vary widely.**

**Figure 8.13.** Pollinator responses to changing climate conditions within a short time frame (the past 10–30 years) are leading to complex patterns of species movements across the landscape. Several species of bumble bees (**panel 1**) have had different responses over the past 10 years, from shifting in habitat within their ranges to range contractions and extinction risks. In **panel 2**, butterfly species are responding with declines and shifts within existing ranges or with range expansions nationwide. Figure credit: Colorado State University.

## Box 8.1. Case Study: Climate Sensitivities of North Atlantic Right Whales

The North Atlantic right whale (*Eubalaena glacialis*) is one of the world's most endangered large whales, primarily due to historical commercial hunting, with fewer than 350 individuals remaining.[135] This species is vulnerable to climate change–driven extinction in part because of its large size, long lifespan, slow growth, delayed maturity, and small number of offspring.[136] Population recovery has been hindered by climate-driven changes in the distribution, availability, and quality of zooplankton, which has altered whale foraging patterns (KM 10.1).[133,137,138] As finding shelter and food becomes more difficult, the whales become more susceptible to disease, fishing gear entanglements, and vessel strikes, contributing to decreased body size and reproductive success (Figure 8.14).[139,140] Loss of these whales can have cascading effects on ecosystem composition and function.[141]

### Threats to North Atlantic Right Whales

**Climate change increases risks to the endangered North Atlantic right whale.**

**Figure 8.14.** The whale known as Snow Cone is shown with her newborn calf near Cumberland Island, Georgia, in 2021. She was entangled in fishing rope for at least two years and is currently presumed deceased. Such threats are exacerbated as whales travel into new feeding areas because of changing oceanographic conditions. Photo credit: ©Georgia Department of Natural Resources/NOAA Permit #20556.

## *Disease Risks*

Disease threats to wildlife, plants, and humans have emerged as a significant climate change risk.[142,143,144,145,146,147] Climate change promotes range expansions and population growth of disease-spreading (vector) species, increased host susceptibility via stress, and enhanced pathogen transmission (Table 8.1; KM 15.1),[148] with major economic consequences.[149,150] Diseases often thrive where other stressors are present; prevalence is projected to further increase as populations and ecosystems become stressed from temperature variation and extreme events, changes in habitats, altered migration patterns and ranges, biodiversity loss, and increases in invasive species (KMs 15.1, 30.4; Figure A4.16).[151,152,153,154]

**Table 8.1. Climate-Impacted Disease Risks in Humans and Wildlife**

Numerous wildlife and human diseases (KM 15.1) are expanding to new areas and species and becoming more common as climate change expands vector ranges and changes species interactions and habitat preferences. Sources: Islam et al. 2022; Gilbert 2021; Ogden et al. 2021; Sonenshine 2018; Keesing and Ostfeld 2021.[152,153,155,156,157]

**Pathogen: Virus**

| Disease | Affected Organisms |
|---|---|
| West Nile virus | Birds and mammals |
| Viral hemorrhagic septicemia virus | Freshwater and marine fish |
| White spot syndrome virus | Aquatic crustaceans |
| Tomato spotted wilt virus | Plants |

**Example of impacts: Viral hemorrhagic septicemia** damages wild and farm-raised fish such as rainbow trout, with patterns of spread and establishment being highly correlated with climatic variables (temperature, precipitation).[158]

**Pathogen: Bacteria**

| Disease | Affected Organisms |
|---|---|
| Furunculosis | Trout and salmon |
| Enteric red mouth disease | Freshwater and marine fish |
| Citrus greening | Plants |

**Example of impacts: Citrus greening** is a bacterial disease transmitted by an invasive insect (Asian citrus psyllid). Because the disease is highly sensitive to temperature, climate change is expected to allow it to spread farther.[159] Since 2005, Florida citrus production has declined 74%.[160]

**Pathogen: Fungus**

| Disease | Affected Organisms |
|---|---|
| White-nose syndrome | Bats |
| Chytridiomycosis | Amphibians |
| Rapid ʻŌhiʻa death | Plants |
| Armillaria root rot | Plants |

**Example of impacts: Rapid ʻŌhiʻa death** is a fungal disease that impacts ʻŌhiʻa lehua, a Hawaiian keystone species with important functional and cultural roles. Large-scale mortality is projected to worsen in a warmer and wetter climate.[161]

**Pathogen: Parasite**

| Disease | Affected Organisms |
|---|---|
| Avian malaria | Birds |
| Proliferative kidney disease | Salmon |
| Brainworm | Moose, elk, caribou |
| Seagrass wasting disease | Aquatic plants |

**Example of impacts: Brainworm** is a parasitic nematode spread via white-tailed deer, which are currently expanding farther northward. In moose, population declines due to brainworm are already affecting subsistence hunting among some Tribal communities.[162]

**Pathogen: Unknown**

| Disease | Affected Organisms |
|---|---|
| Stony coral tissue loss disease | Corals |
| White band disease | Corals |
| Colony collapse disorder | Bees |

**Example of impacts: Stony coral tissue loss disease** originated in Florida in 2014 and has spread throughout the Caribbean, with thermal stress implicated in reef vulnerability. The disease affects more than 30 coral species, including many important reef-builders. Rapid spread and high mortality rates have had serious economic consequences for tourism and fishing.[163]

## *Invasive Species Risks*

Climate change has created uncertainty about where and how fast invasive species will spread, but there are both observed cases[164] and projections showing expected increases.[165] For example, cold-sensitive invasive species such as the kudzu vine (*Pueraria montana* var. *lobata*) can spread northward with warming.[166] Some invasive species are more successful than natives—particularly certain terrestrial plants[167] and aquatic species[168]—because they better tolerate or more rapidly adapt to changing conditions (Figure 8.15). Yet not all invasive species are favored by climate change; many invasive plants and vertebrates may experience decreased ranges while the ranges of many invasive invertebrates and pathogens are expected to increase.[169]

### Invasive Species and Climate Change

**Damaging invasive species that are expected to shift in range because of climate change.**

**Figure 8.15.** Examples of invasive species include the following: (**a**) Hemlock woolly adelgid, an insect pest, is expected to spread northward with warmer winters and cause die-offs of eastern hemlock trees.[170] (**b**) Invasive carp are expected to benefit from warmer waters and expand into the Great Lakes, where they will compete with native fishes and present boating hazards through their habit of jumping out of the water.[171] (**c**) Eurasian watermilfoil chokes freshwater systems and outcompetes natives in warmer conditions.[172] (**d**) European green crabs, which benefit from warmer waters, harm economically important native shellfish fisheries.[173] Photo credits: (a) Kerry Wixted via Flickr [CC BY-NC 2.0]; (b) Steve Hillebrand, USFWS; (c) ©Stephen K. Hamilton, Cary Institute of Ecosystem Studies; (d) ©P. Sean McDonald, University of Washington.

## *Assisting Species Adaptation*

Natural resource managers are implementing adaptation actions including increasing conservation efforts, reducing habitat fragmentation, protecting wildlife corridors, assisting species migration, and expanding protection activities.[174] For example, marine protected areas can reduce non-climate stressors like overfishing and facilitate recovery of populations following extreme events like heatwaves, which then benefits recreational and commercial fishing in surrounding areas (KM 28.2).[175] Many states now include climate impacts in state wildlife action plans; for example, Massachusetts has identified habitat patches allowing for movement of the threatened Blanding's turtle and is creating habitats that balance increased drought and other threats.[176,177,178]

Managing for connectivity can enhance species climate resilience, particularly for wide-ranging and migratory species.[179] Priorities include connecting climate refugia, areas of high diversity,[123,180] and current and future habitat types.[181] For example, resilience strategies for the saltmarsh sparrow (*Ammospiza caudacuta*), which has declined dramatically due to rising sea levels, include protection of areas expected to convert into future wetlands, use of runnels and other elevation manipulations, and high-marsh restoration.[182,183]

Assisted migration has been implemented for at-risk species such as the Laysan albatross, Oʻahu tree snail, relict leopard frog, and wolf (Figure 8.16).[184] In the Chippewa National Forest in Minnesota, seeds of tree species native to red pine forests but collected 100–200 km to the south—and thus genetically distinct from local populations—are being planted to test assisted migration.[185]

### Managing for Species Adaptation

**Assisted migration can help species adapt to changing climate conditions.**

**Figure 8.16.** One example is the translocation of wolves to Isle Royale National Park, Michigan. The loss of ice bridges in winter prevented new arrivals that would have maintained genetic viability of the population.[186] Photo credit: Jacob W. Frank, NPS.

### *Implications for Management*

While protected areas can help species adapt to climate change, these areas are themselves vulnerable;[174,187,188,189] many US protected areas are expected to see major shifts in vegetation communities and other species.[190] Further, the existing US protected areas system has low overlap with projected climate refugia;[191] extending protection to include future habitat suitability for some species may double costs.[192] Given continued range shifts, areas with priority species that draw tourists (e.g., bird watchers) will need to refocus as some species become rarer or disappear,[193,194] impacting neighboring communities dependent on tourism revenue.

Conflicts (between humans and with wildlife) arising from climate-driven changes in distribution and availability of species and resources are occurring.[195,196] For example, some species are moving out of areas set up to conserve them, and range shifts of fish stocks (including across international boundaries) are causing challenges (KM 10.1).[197,198] Some adaptation policies (e.g., translocation of nonhuman species into human communities unwilling to coexist with them) may exacerbate conflicts (KM 17.2).[199] Adaptive management that prioritizes both climate change response planning and conflict management can reduce negative outcomes.[195,200,201]

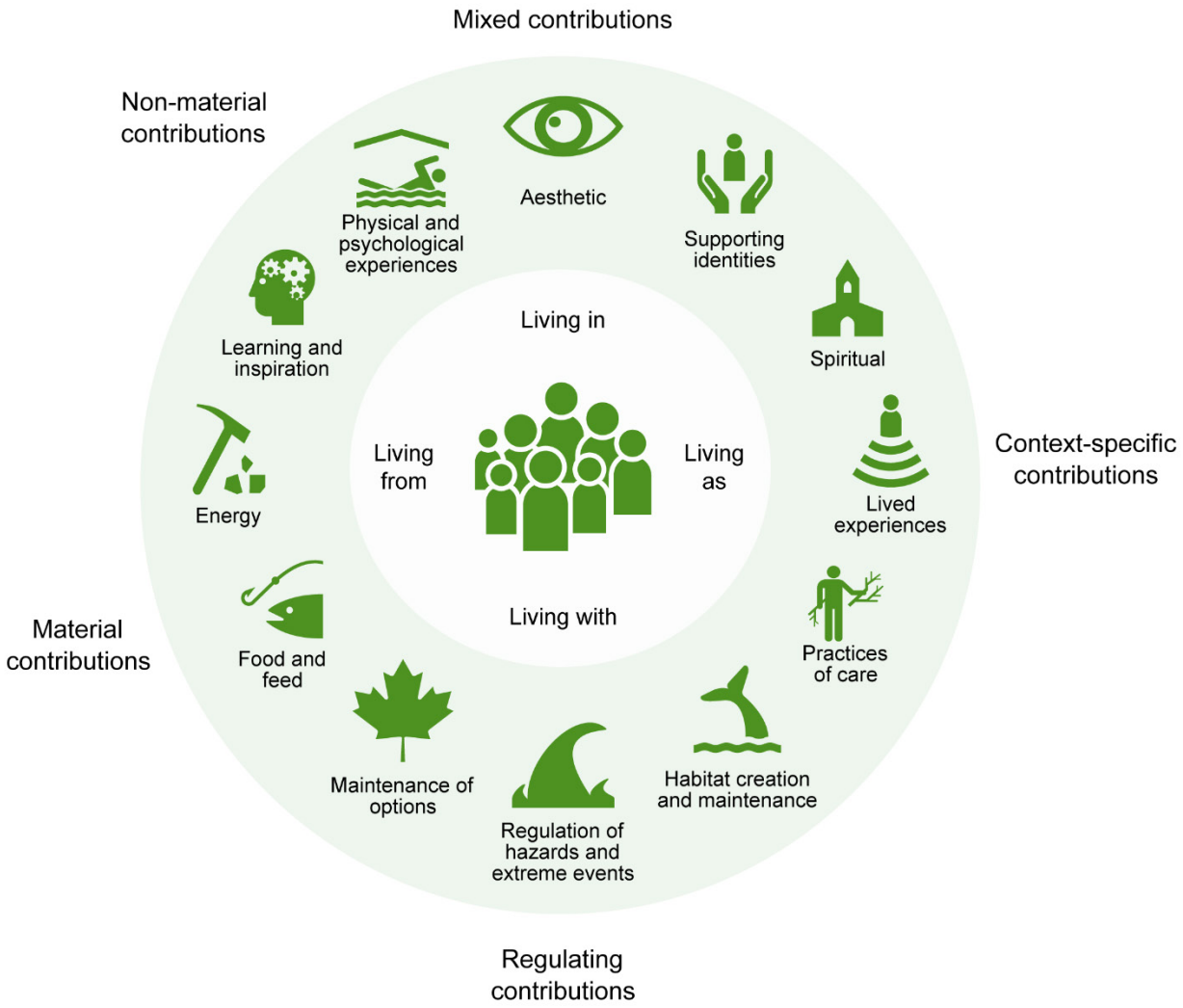
## Key Message 8.3

## Impacts to Ecosystem Services Create Risks and Opportunities

Climate change is having variable and increasing impacts on ecosystem services and benefits, from food production to clean water to carbon sequestration, with consequences for human well-being (*very likely*, *high confidence*). Changes in availability and quality of ecosystem services, combined with existing social inequities, have disproportionate impacts on certain communities (*very likely*, *high confidence*). Equity-driven nature-based solutions, designed to protect, manage, and restore ecosystems for human well-being, can provide climate adaptation and mitigation benefits (*likely*, *medium confidence*).

Ecosystem services provide substantial and often economically important contributions to communities, ranging from direct material benefits like food production and clean water to nonmaterial benefits like recreation (Figure 8.17). However, economic valuation alone does not reflect intrinsic or relational values that people hold toward nature;[202,203] for example, Tribal and Indigenous Peoples rely on ecosystems for supplies of culturally valuable food, materials for religious ceremonies, and relational links within communities and among generations (KM 16.1).[204,205]

## Ecosystem Services and Their Benefits




**Ecosystems provide a broad range of relational benefits, from the material to the spiritual.**

**Figure 8.17.** Ecosystem services, also called "nature's contributions to people," are the benefits that humans receive or derive from ecosystems. These are both material (e.g., energy sources) and non-material (e.g., sense of place), and contribute to the regulation of ecosystem processes. The broad categories of benefits pictured are fluid and overlapping. People value nature in multiple ways, such as "living as" nature (e.g., Indigenous viewpoints that humans are part of the environment; Figure 16.3) or "living from" nature (e.g., people's dependency on key services). Adapted from O'Connor and Kenter 2019[206] [CC BY 4.0].

There are many adverse climate change effects on ecosystem services,[207,208] including reduced water availability for human and agricultural uses (KM 4.1), decreased productivity of crop species due to increased pest infestations (KM 11.1), and losses of hazard-mitigating ecosystems like wetlands and coastal shorelines that provide nursery and nesting habitat, recreation, and aesthetic pleasure (Table 8.2; KM 9.2). However, future trends on ecosystem use and benefits are not always clear. For example, rising temperatures can extend seasonal recreational opportunities, but if daily high temperatures exceed 27°–30°C (80.6°–86°F), recreation tends to decrease.[209,210]

Further, diminished benefits from ecosystem services can also occur based on other factors.[211,212] For example, discriminatory planning practices, housing segregation, and racism have created inequitable distributions of services, leading to communities of color experiencing reduced access to benefits like improved air quality or heat reduction (KM 12.2; Figure 12.6).[213,214,215] Lack of access often accompanies other environmental harms (e.g., greater exposure to allergens or risks of green gentrification, the displacement of local residents as environmental benefits improve).[216,217] Climate change is expected to exacerbate these impacts[207] and create further difficulties in addressing environmental racism, highlighting the need for clear management priorities and recognition of diverse values.[218,219]

**Table 8.2. Examples of Climate Impacts on Ecosystem Services**

Climate change affects the availability and quality of many ecosystem services, and many projected impacts on important ecosystem services will also have equity implications.

| Ecosystem Service | Potential Climate Impacts | Equity Implications |
|---|---|---|
| **Regulation of Natural Hazards** | Coastal marsh retreat is projected due to sea level rise and increased storm activity.[220] | Flood risks are often inequitably distributed; for example, property damage risks can be disproportionately higher for Black communities.[221] |
| **Physical and Psychological Experiences** | Cold-weather recreational opportunities are projected to decline (e.g., fewer skiing days).[209,210,222] | Less green space access in low-income communities and communities of color already results in fewer opportunities for recreation.[223,224] |
| **Water Quantity** | Changes in precipitation, snowpack, soil moisture, and evapotranspiration are projected to alter surface and groundwater availability (KM 4.1; Figure A4.7). | Drought often has disparate impacts;[225] for example, Tribal reservations in the US Southwest with higher agricultural dependence will be particularly impacted.[226] |
| **Regulation of Air Quality** | Street trees provide considerable urban air quality benefits but are vulnerable to drought and heat.[227] | Existing tree canopy distribution is inequitable, accounting for greater air pollution[228,229,230] associated with legacies of redlining.[231] |
| **Food Production (fisheries)** | Aquatic systems are experiencing shifts in species ranges, phenologies, distributions, and productivities.[232] | Culturally important species, such as Chinook salmon for Pacific Northwest Tribes, are projected to dramatically decline in the future.[233] |

## *Opportunities for Nature-Based Solutions*

Ecosystem-based mitigation and adaptation opportunities are often called nature-based solutions (NBSs) or natural climate solutions (Figure 8.18).[234,235] NBSs support biodiversity and can provide other benefits when managed in collaboration with affected communities and use of local knowledge (KM 21.1). For example, coastal wetland restoration provides both mitigation and adaptation benefits by sequestering carbon and decreasing coastal flooding, wave action, and erosion[236] while improving water quality and increasing habitat biodiversity (KM 9.3; Focus on Blue Carbon).[237] NBS projects are often very cost-effective, spurring new financing options.[238,239]

Ecosystem-based adaptation is a type of NBS aimed at increasing community resilience to climate change through the use of ecosystems.[240,241] Examples include protecting and restoring floodplains to help reduce flood impacts[242] or helping farmers cope with drought through soil conservation measures.[243] There are high returns on investments to restore coastal ecosystems in particular, since US coral reefs provide estimated adaptation benefits of more than $1.8 billion annually (dollar year not provided).[244,245] These approaches can also have positive equity benefits when designed with local participation and buy-in through collaborative approaches (KM 31.4).[246,247,248,249,250,251]

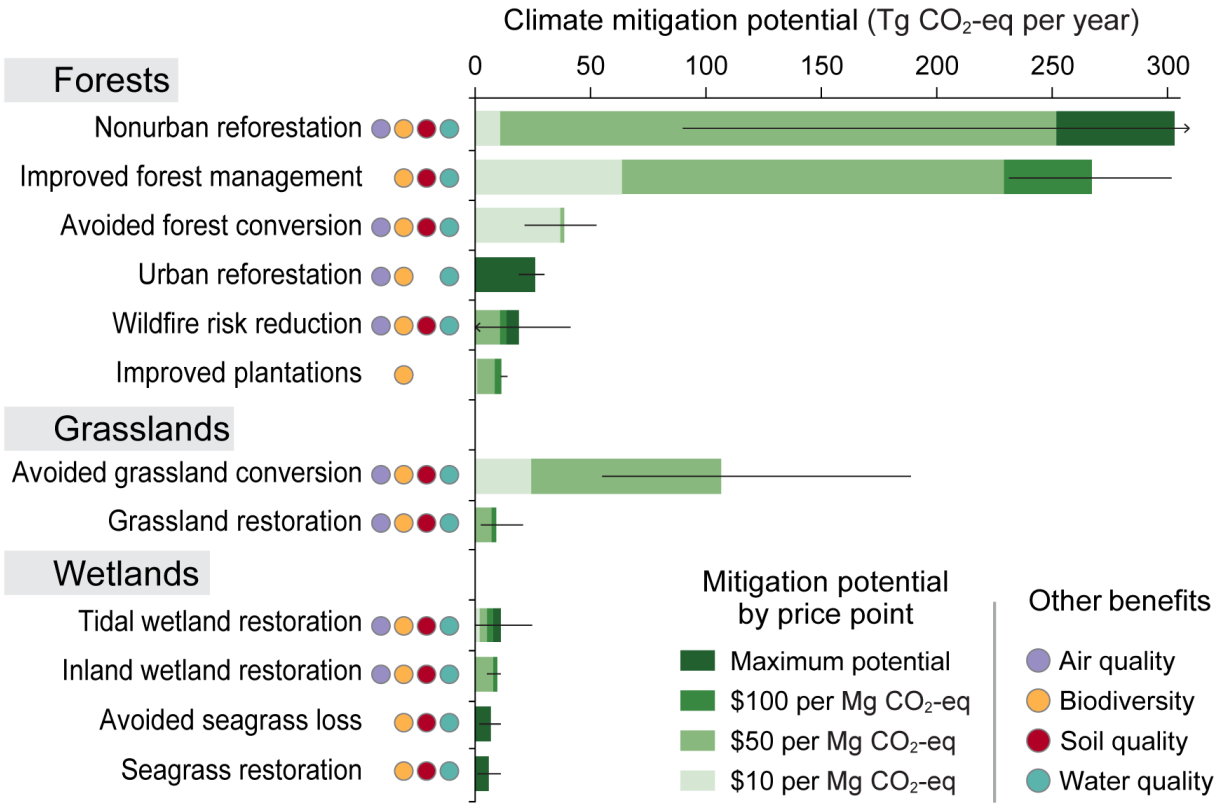
## Nature-Based Solutions

**Nature-based solutions buffer the effects of climate change.**

**Figure 8.18.** Nature-based solutions (NBS) are actions to protect, manage, and restore ecosystems to address societal challenges such as climate change. Examples in the US include (**a**) oyster restoration; (**b**) cover cropping; (**c**) stormwater management; and (**d**) urban agriculture. These not only help buffer the impacts of climate change, such as through physical barriers or improved local microclimates, but also provide additional benefits like food and habitat provisioning.[252,253,254] Figure credit: Rutgers University and NPS. See figure metadata for additional contributors. Photo credits: (a) Linda Walters, NPS; (b) David Bosch, USDA; (c) Alisha Goldstein, EPA; (d) Bob Nichols, USDA.

Current and future opportunities for NBSs exist across the US, particularly for mitigation solutions focused on protecting and increasing carbon storage by natural ecosystems (Figures 6.6, 8.19; Focus on Blue Carbon).[255] Planning for future protected areas for both climate and biodiversity could emphasize areas that not only hold large amounts of carbon but also help species adapt,[256] recognizing the important role that many animal species play in carbon cycling.[257] However, NBSs themselves are also vulnerable to rising temperatures, sea level rise, and other climate impacts.[258]

## Climate Mitigation Potential of Nature-Based Solutions in 2025




**Nature-based solutions can support carbon storage while also providing other benefits.**

**Figure 8.19.** Nature-based solutions (NBSs) can preserve or enhance carbon storage in soils and biomass across natural systems like forests, grasslands, and wetlands, as well as agricultural lands. Different approaches vary in their climate mitigation potential, shown here as teragrams of carbon dioxide equivalent (Tg $CO_2$-eq per year; length of bars) in the year 2025. Lighter green shades indicate the estimated portion of mitigation obtainable for less than $10, $50, or $100 per megagram of $CO_2$-eq (Mg $CO_2$-eq). The dark green "Maximum" category shows the highest technical carbon sequestration potential that is also consistent with meeting human needs for food and fiber. Black lines are error bars indicating either the 95% confidence interval or an uncertainty range, depending on the source of the estimate. The arrow indicates a range that may exceed the values shown on the chart. Other potential benefits of NBSs are also indicated for each category (colored dots). Figure addresses contiguous US only. Adapted from Fargione et al. 2018[259] [CC BY 4.0].

NBSs that involve restoring degraded ecosystems can improve resilience[260] and increase provision of ecosystem services.[261] Ideally, restoration is designed to recover a range of potential benefits.[262,263] However, multiple services cannot necessarily be maximized simultaneously, as focusing on one ecosystem service at the expense of other benefits leads to trade-offs.[264,265,266] Larger-scale restoration efforts are generally more successful when connected to local priorities,[267] including their use in addressing environmental inequities (Box 8.2).[268]

## Box 8.2. Restoration and Ecosystem Management by Tribal Nations

Tribal forestry programs throughout the US provide exemplary models of Indigenous land management practices that showcase Tribes' ability to balance sustainable environmental stewardship, fulfilling the social, ecological and economic needs of their communities.[269] The "anchor forests" concept, in which Tribes are at the center of multiple landownerships and serve as the primary hub for providing forest management infrastructure, is one effective approach. Such initiatives maximize concepts of Tribal sovereignty and Indigenous Knowledge to restore forests at the pace and scale needed to mitigate and adapt to rapid climate change.[270] Furthermore, traditional and contemporary Indigenous management practices that support both cultural and spiritual relationships with nature and an equitable climate transition can serve as critical pathways to sustaining ecosystems (KMs 7.3, 16.1).[271] Incorporating local knowledge and Indigenous Peoples in the co-development of restoration activities can produce considerable benefits.[272]

# Traceable Accounts

## *Process Description*

The chapter lead author, coordinating lead author, and agency chapter lead authors discussed the Fourth National Climate Assessment (NCA4) ecosystems chapter and brainstormed topics that had emerged since then or were not well covered. The chapter lead author also pulled out key gaps identified from the US Global Change Research Program assessment review document and public comments. A tentative list was compiled of authors with expertise in ecosystems, biodiversity, and ecosystem services; marine, freshwater, and terrestrial systems covering NCA regions; and ecosystem types. The final author team comprised a mix of federal agency scientists and academic experts with varying experience in assessments and past NCAs. Key Messages were developed by the full author team through virtual meetings from fall 2021 through spring 2022, with additional inputs from a public engagement workshop held in January 2022, in which over 100 people participated virtually to suggest topics for review by the chapter. A Youth Dialogues public engagement workshop was held online in February 2022 in partnership with the Youth Environmental Alliance in Higher Education and Rutgers Climate Institute. Federal agency reviews in summer 2022 provided further suggestions for improvement, as did additional public comments and the National Academies review in spring 2023. At the April 2023 in-person meeting in Washington, DC, the author team collectively discussed the wording and confidence levels for the three Key Messages to ensure consensus around the statements.

Since NCA4, a plethora of research has been published describing how ecosystems are changing or are expected to change further in the face of climate change and other stressors, along with numerous specific species and ecosystem services impacts. The evidence base for this report is therefore heavily weighted to peer-reviewed journal articles published in the last five years.

## Key Message 8.1

## Climate Change Is Driving Rapid Ecosystem Transformations

### Description of Evidence Base

#### Ecosystem Regime Shifts

Many examples of regime shifts resulting from transformative changes are already documented, and the evidence base is strong across multiple ecosystem types,[273] including forest transformations to grassland or woodland following increased wildfires; widespread die-off of pinyon pines from drought and bark beetle infestations; and shifts from healthy kelp forests to urchin barrens due to epizootic disease and marine heatwaves in nearshore marine environments.[144,274,275,276,277,278,279,280] Overall, regime shifts of temperate ecosystems toward more subtropical ones at their southern limits are expected in response to future decreases in the frequency and intensity of extreme cold events.[45] For example, mangrove forests in Florida and along the Gulf Coast are projected to expand northward into present-day salt marshes.[43]

### Monitoring

Systematic biodiversity surveys, digitized museum records, and long-term automated data collection have all demonstrated the importance of multiple methods of monitoring of environmental changes through strong evidence bases.[281,282,283,284]

## Major Uncertainties and Research Gaps

### Complexity of Impacts on Ecosystems

The ability to predict ecological responses to changing climate conditions remains a key gap for most ecosystems because of complex interactions among species, the potential for adaptation (through both evolutionary responses and human activity), and the intersection of climate change with other drivers of change.[36,285,286] For example, warmer temperatures can lead not only to increased forest regeneration and tree growth but also to increased mortality of older trees through wildfires, insects, and disease, with the resulting net impacts highly uncertain.[287] Warmer winters are generally expected to benefit forest pests,[288] but complex interactions among pests, their hosts, and other disturbances can make the combined effects more muted than otherwise expected.[289,290,291] Recent research suggests that multiple disturbances can have counteracting effects, although patterns are not always clear, and sometimes intensified combined effects (synergies) also occur.[292,293]

### Monitoring

There are a number of gaps in comprehensive, long-term ecological monitoring to detect changes and to predict the risks of future climate change.[48] Improved knowledge of biological response mechanisms that drive ecological changes[36] will enable better anticipation of ecosystem shifts, especially for systems dominated by long-lived species and where impacts emerge after a time lag;[294,295] this makes eliminating monitoring gaps (e.g., in Arctic and ocean regions) critical. Community monitoring programs are promising but can be biased (e.g., lack of uniform sampling) toward particular regions or species.[296]

### Adaptive Management

While adaptive management is widely considered an effective approach for managing uncertainty through learning in order to conserve, manage, and restore ecosystems and species populations,[297] successful implementation is limited by the lack of effective monitoring mechanisms,[298] challenges in dealing with uncertainty, and lack of appropriate institutional mechanisms for its implementation, among other problems.[299,300,301,302] As a result, an adaptive governance approach is increasingly understood as a broader and more promising mechanism for addressing the social and institutional requirements of adaptive management while also facilitating social–ecological transformation.[300,303] However, the adaptive governance approach also has its own conceptual and implementation challenges that need to be addressed in order to enhance success, given insufficient evidence on effective implementation[298] and questions about its capacity to bring about transformational changes.[304] There is also potential for undesirable outcomes, such as inadequate consideration of power and social equity issues.[305,306,307,308] Moreover, there are gaps in research on enhancing the transition process toward adaptive management and governance and associated outcomes,[309] as well as lack of clarity on the synergies and trade-offs among determinants of the capacity for adaptation and transformation.[310,311]

## Description of Confidence and Likelihood

A growing body of empirical field studies and monitoring programs shows that climate change, in concert with other stressors, is driving transformational changes across many ecosystems and that changes will accelerate with continued warming (*very likely*, *high confidence*). Given the growing impacts of ecosystem change, the serious implications for human well-being were also considered *very likely*, and the authors assessed *high confidence*, given the empirical studies across multiple ecosystems (i.e., not just projections)

showing that a range of well-being impacts are already being experienced across economic, cultural, and social systems. As Chapter 2 has indicated, extreme events are increasing in frequency and/or severity, and these events are more frequently implicated in abrupt ecosystem changes; but because of limited studies examining the direct correlation of extreme events on abrupt ecosystem transformations, the authors assessed only *medium confidence*. The authors also note that adaptive governance frameworks, adaptive management, and monitoring all play a role in helping to cope with climate changes; but given the paucity of evidence of long-term impacts of adaptive governance, the authors assessed only *medium confidence*.

## Key Message 8.2

## Species Changes and Biodiversity Loss Are Accelerating

### Description of Evidence Base

#### Range Shifts

Shifts in species ranges in response to changing climate occur across a wide range of species and are expected to accelerate.[312,313] The evidence base is strong across a wide range of marine, plant, invertebrate, reptile, bird, and mammal species; selected examples are shown in Figure 8.11, but many more exist. Further, there is strong evidence for the patterns of range shifts differing among types of species; for example, multiple studies have shown that marine species have expanded their ranges more readily than terrestrial species, with shifts in distributions occurring more quickly as well,[314,315] whereas terrestrial species tend to have greater behavioral adaptations and less physiological sensitivity to temperature changes.[316,317,318]

#### Phenological Changes

The evidence base of documented responses in the timing of life cycles to climate change is strong, ranging from earlier flowering dates in many parts of the country, to shifts in hibernation of mammals, to timing of egg laying of frogs.[319,320] Very rapid changes can be easily observed, for example, in short-lived plants that have high turnover rates and more rapid genetic adaptation,[321] lending strength to the evidence base.

#### Extinction Risks

Long-term studies (i.e., decades) are needed to discern the fingerprints of climate change on long-lived animals,[322] which can be challenging. But some impacts are in evidence; for example, sea level rise is expected to impact nesting site availability and quality for sea turtles, while warming temperatures can affect sex ratio of offspring.[323,324] Refugia have potential to mitigate some extinction risks for species able to take advantage of them, but the evidence base is fairly new. Further, emerging modeling studies have indicated that these areas, too, are at risk; for example, Ebersole et al. (2020)[127] found that under a 4°C (7.2°F) warming scenario, there was a >50% probability that refugia for freshwater fish species would decrease in area by 42%–77% by 2070.

#### Disease Risks

Disease risks are occurring as a result of many factors and across different hosts and pathogens; given the large number of potential risks, meta-analyses have been helpful in providing overviews of the evidence base. One comprehensive review of infectious diseases spread between humans and animals found that 58% of diseases worldwide have been exacerbated by climate change (e.g., warming, altered precipitation, and floods).[154] Only 16% of diseases were diminished by climate change. A global analysis of thousands of wildlife populations indicated that climate warming exacerbates wildlife disease throughout the temperate zone worldwide and is expected to increase wildlife disease in the United States.[325] A different global analysis of 6,801 ecological assemblages demonstrated that human-dominated ecosystems strongly favored animal

species that host human disease pathogens while decreasing the presence of non-host animals,[326] a strong evidence base for the finding that stressed ecosystems tend to experience more disease risk.[153] Many empirical examples of ongoing disease outbreaks—e.g., fish kills and large-scale coral disease outbreaks following coral bleaching events—have increased in number and are evidence of perturbed aquatic systems where disease stresses are exacerbated by warming.[144,146] The well-documented catastrophic declines in amphibian populations caused by the invasive chytrid fungus *Batrachochytrium dendrobatidis* have also been well linked to warming conditions.[327]

## Major Uncertainties and Research Gaps

### Range Shifts

The speed and extent of some species range shifts remain uncertain. Climate envelope models use current relationships among species ranges and climatic characteristics to project how ranges may shift in the face of climate change,[328] yet they necessarily assume that climate is the main constraint on ranges and that species rapidly respond. In reality, species responses can be slowed and limited by dispersal ability, natural and human-created barriers, and species interactions.[329,330]

Moreover, climate change is expected to present organisms with novel environmental conditions, making predictions based on historical relationships problematic.[331] Specifically, improving such predictions would require a better understanding of the degree to which range shifts occur due to longer-term climatic changes versus periodic extreme weather events such as heatwaves brought on by those climatic changes.[86]

While climate refugia are increasingly discussed in the literature, they are themselves vulnerable to climate impacts, and there is uncertainty about their persistence and resilience.[126,127]

### Phenological Changes

The individual and variable responses of species to climate change is expected to disrupt important biological interactions. Many risks posed by emerging mismatches among interacting species remain unclear,[332] as do needed management responses to reduce economic and social impacts.

### Diseases and Invasives

Impacts of climate change on species health are complex and difficult to generalize across systems;[291] for example, the role of climate change among other drivers of the spread of tick-borne diseases, like changes in land use or human behavior, remains a topic of some debate.[152,156]

Studies showing that invasives could be limited in response to climate change are based mostly on studies of terrestrial species whose range shifts are often limited by oceans,[169] indicating that more research is needed on different types of species to improve projections.

## Description of Confidence and Likelihood

There is *high confidence* that the interaction of climate change with other stressors will *very likely* lead to biodiversity loss, changes in species distribution and life cycles, and increasing impacts from invasives and diseases, given a very well-documented range of species changes across multiple ecosystem types, as well as clear economic and social consequences in many regions already experiencing these impacts. The evidence is strong, and the authors assessed *high confidence* that some species, particularly those that cannot easily relocate and those that are highly temperature sensitive, are facing heightened extinction risks, and that these are *very likely*, given that some species populations are already in serious decline at current levels of warming. Policy actions to help species adapt were assessed, and what they have in common is a clear identification of risks and prioritization of species and locations for protection. The

evidence base for these policy actions is clear, and the authors have *high confidence* that such actions can expand and improve options for management.

## Key Message 8.3

## Impacts to Ecosystem Services Create Risks and Opportunities

### Description of Evidence Base

#### Access to Ecosystem Services

There is strong evidence that communities of color experience greater air pollution inequity[228,229,230,231] compared to White communities and have reduced and/or less high-quality access to green space, trees, and other ecosystems that buffer these impacts. Limited access to resources and services also extends to those with limited income or wealth (also known as economic capacity), and these factors interact with race and other social hierarchies, including power, in complex ways.[333]

#### Climate Impacts on Ecosystem Services

There is strong evidence at the global level that warming and carbon dioxide fertilization effects have already altered some ecosystem services, such as coastal carbon storage and ecosystem biodiversity, as noted in the recent Intergovernmental Panel on Climate Change report.[2] For the US, while not all ecosystem services have been quantitatively assessed for climate impacts, those that have been show either currently observable declines (e.g., nearly 40% of pollinator-dependent crops in the US suffer from low pollinator abundance)[334] or projections of future decline (e.g., reduced outdoor recreation opportunities by 2050).[210]

#### Restoration

Evidence for the effectiveness of restoration at improving ecosystem service benefits is growing as more landscape-scale restoration is undertaken across multiple ecosystems.[263] Additionally, valuation of ecosystem services benefits has proven to be a strong driver of new restoration programs, as it helps identify potential ecosystems to manage or restore (e.g., how health benefits can be obtained from restoration of vegetated terrestrial systems).[262]

### Major Uncertainties and Research Gaps

#### Measurement, Valuation, and Management of Ecosystem Services

There remain challenges in measuring, monitoring, and evaluating the impacts and effectiveness of many ecosystem services.[335] In the US, urban spaces continue to be under-researched, especially in communities of color, despite often being biodiverse environments;[336] and current research is usually limited to city-specific case studies of ecosystem services measurements and analyses, with less focus on comparative work.[248,337] Furthermore, many city planning documents do not include climate change adaptation practices regarding cultural services or environmental injustice in ways that translate to implementation[338] and instead focus on physical and natural resources, costs, or logistics.[247] Research that engages communities, residents, and small organizations in identifying and designing measurements, valuation, and management criteria is a persistent gap, given the continuing lack of resident participatory research and community science in identifying problems and implementing solutions. A few studies have connected multiple types of urban ecosystem services from a theoretical planning point of view,[248,337,339] but integrating justice into ecosystem service practices by prioritizing community needs, aligning methods of assessment and criteria to goals, and addressing environmental racism is a critical gap.[247]

### Restoration

There are few examples of ecological restoration practices designed to be resilient to climate change,[340,341] with particular challenges around making decisions about what needs to be "restored"[342] and to what conditions or baseline, as well as how to minimize vulnerability to extreme climate events that may be unprecedented in recent history. There can be spatial disconnects between where restoration actions need to be implemented and where ecosystem service improvements will be observed,[343] and the economic cost of restoration efforts and stakeholder preferences for desired states can prevent recovery efforts.[344]

### Nature-Based Solutions (NBSs)

NBSs could cause risks of undesirable outcomes if they entail ecosystem transformations or species introductions over large areas of land; thus, they require careful study prior to implementation to avoid exacerbation of environmental and social injustices.[345,346] There are increasing cases of poorly designed NBSs and rising concern over second-order effects, like green gentrification.[216,217] However, there are considerable research gaps regarding how to avoid these outcomes. Evidence suggests that more stakeholder engagement in carbon removal projects and policies could help maximize adaptation benefits,[347] but this is an area of ongoing research.

## Description of Confidence and Likelihood

There is *high confidence* that climate is having variable and growing impacts on many ecosystem services, based on an expanding literature containing many regional examples. These changes are assessed as *very likely*, given the existing levels of warming in areas where impacts have already been observed. There is *high confidence* that these changes in availability and quality of ecosystem services, when combined with existing social inequities that are also well documented, will result in disproportionate impacts on some communities. These disproportionate impacts were assessed as *very likely*, given that impacts are already visible, particularly in urban areas. The authors assessed it to be *likely* that nature-based solutions designed to be equitable can provide multifunctional benefits for climate adaptation and mitigation, although there is only *medium confidence* that current examples of nature-based solutions are able to fully address mitigation and adaptation needs in an equitable manner, given a growing body of evidence that poorly designed or inequitable nature-based solutions do continue to be implemented in some places.

# References


1. IPBES, 2019: *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Díaz, S., J. Settele, E.S. Brondízio, H.T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K.A. Brauman, S.H.M. Butchart, K.M.A. Chan, L.A. Garibaldi, K. Ichii, J. Liu, S.M. Subramanian, G.F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y.J. Shin, I.J. Visseren-Hamakers, K.J. Willis, and C.N. Zayas, Eds. IPBES Secretariat, Bonn, Germany, 56 pp. https://www.ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf

2. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–33. https://doi.org/10.1017/9781009325844.001

3. Pecl, G.T., M.B. Araújo, J.D. Bell, J. Blanchard, T.C. Bonebrake, I.-C. Chen, T.D. Clark, R.K. Colwell, F. Danielsen, B. Evengård, L. Falconi, S. Ferrier, S. Frusher, R.A. Garcia, R.B. Griffis, A.J. Hobday, C. Janion-Scheepers, M.A. Jarzyna, S. Jennings, J. Lenoir, H.I. Linnetved, V.Y. Martin, P.C. McCormack, J. McDonald, N.J. Mitchell, T. Mustonen, J.M. Pandolfi, N. Pettorelli, E. Popova, S.A. Robinson, B.R. Scheffers, J.D. Shaw, C.J.B. Sorte, J.M. Strugnell, J.M. Sunday, M.-N. Tuanmu, A. Vergés, C. Villanueva, T. Wernberg, E. Wapstra, and S.E. Williams, 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355** (6332), eaai9214. https://doi.org/10.1126/science.aai9214

4. Finney, C., 2014: *Black Faces, White Spaces: Reimagining the Relationship of African Americans to the Great Outdoors*. UNC Press, Chapel Hill, NC. https://uncpress.org/book/9781469614489/black-faces-white-spaces/

5. Whyte, K., 2020: Too late for Indigenous climate justice: Ecological and relational tipping points. *WIREs Climate Change*, **11** (1), e603. https://doi.org/10.1002/wcc.603

6. Weiskopf, S.R., M.A. Rubenstein, L.G. Crozier, S. Gaichas, R. Griffis, J.E. Halofsky, K.J. Hyde, T.L. Morelli, J.T. Morisette, R.C. Muñoz, A.J. Pershing, D.L. Petersone, R. Poudel, M.D. Staudinger, A.E. Sutton-Grier, L. Thompson, J. Vose, J.F. Weltzin, and K.P. Whyte, 2020: Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, **733**, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782

7. Prober, S.M., V.A.J. Doerr, L.M. Broadhurst, K.J. Williams, and F. Dickson, 2019: Shifting the conservation paradigm: A synthesis of options for renovating nature under climate change. *Ecological Monographs*, **89** (1), e01333. https://doi.org/10.1002/ecm.1333

8. Lipton, D., M. Rubenstein, S.R. Weiskopf, S. Carter, J. Peterson, L. Crozier, M. Fogarty, S. Gaichas, K.J.W. Hyde, T.L. Morelli, J. Morisette, H. Moustahfid, R. Muñoz, R. Poudel, M.D. Staudinger, C. Stock, L. Thompson, R. Waples, and J.F. Weltzin, 2018: Ch. 7. Ecosystems, ecosystem services, and biodiversity. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 268–321. https://doi.org/10.7930/nca4.2018.ch7

9. Panetta, A.M., M.L. Stanton, and J. Harte, 2018: Climate warming drives local extinction: Evidence from observation and experimentation. *Science Advances*, **4** (2), 1819. https://doi.org/10.1126/sciadv.aaq1819

10. Román-Palacios, C. and J.J. Wiens, 2020: Recent responses to climate change reveal the drivers of species extinction and survival. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (8), 4211–4217. https://doi.org/10.1073/pnas.1913007117

11. Parmesan, C., M.D. Morecroft, Y. Trisurat, R. Adrian, G.Z. Anshari, A. Arneth, Q. Gao, P. Gonzalez, R. Harris, J. Price, N. Stevens, and G.H. Talukdarr, 2022: Ch. 2. Terrestrial and freshwater ecosystems and their services. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 197–377. https://doi.org/10.1017/9781009325844.004

12. Warren, R., J. Price, E. Graham, N. Forstenhaeusler, and J. VanDerWal, 2018: The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science*, **360** (6390), 791–795. https://doi.org/10.1126/science.aar3646

13. Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas, 2009: Ocean acidification: The other $CO_2$ problem. *Annual Review of Marine Science*, **1** (1), 169–192. https://doi.org/10.1146/annurev.marine.010908.163834

14. Bradford, J.B., J.L. Betancourt, B.J. Butterfield, S.M. Munson, and T.E. Wood, 2018: Anticipatory natural resource science and management for a changing future. *Frontiers in Ecology and the Environment*, **16** (5), 295–303. https://doi.org/10.1002/fee.1806

15. Malhi, Y., J. Franklin, N. Seddon, M. Solan, M.G. Turner, C.B. Field, and N. Knowlton, 2020: Climate change and ecosystems: Threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190104. https://doi.org/10.1098/rstb.2019.0104

16. Reside, A.E., N. Butt, and V.M. Adams, 2018: Adapting systematic conservation planning for climate change. *Biodiversity and Conservation*, **27** (1), 1–29. https://doi.org/10.1007/s10531-017-1442-5

17. Harris, R.M.B., L.J. Beaumont, T.R. Vance, C.R. Tozer, T.A. Remenyi, S.E. Perkins-Kirkpatrick, P.J. Mitchell, A.B. Nicotra, S. McGregor, N.R. Andrew, M. Letnic, M.R. Kearney, T. Wernberg, L.B. Hutley, L.E. Chambers, M.S. Fletcher, M.R. Keatley, C.A. Woodward, G. Williamson, N.C. Duke, and D.M.J.S. Bowman, 2018: Biological responses to the press and pulse of climate trends and extreme events. *Nature Climate Change*, **8** (7), 579–587. https://doi.org/10.1038/s41558-018-0187-9

18. Zhou, S., B. Yu, and Y. Zhang, 2023: Global concurrent climate extremes exacerbated by anthropogenic climate change. *Science Advances*, **9** (10), 1638. https://doi.org/10.1126/sciadv.abo1638

19. Ibanez, T., W.J. Platt, P.J. Bellingham, G. Vieilledent, J. Franklin, P.H. Martin, C. Menkes, D.R. Pérez-Salicrup, J. Russell-Smith, and G. Keppel, 2022: Altered cyclone–fire interactions are changing ecosystems. *Trends in Plant Science*, **27** (12), 1218–1230. https://doi.org/10.1016/j.tplants.2022.08.005

20. Smith-Martin, C.M., R. Muscarella, R. Ankori-Karlinsky, S. Delzon, S.L. Farrar, M. Salva-Sauri, J. Thompson, J.K. Zimmerman, and M. Uriarte, 2022: Hurricanes increase tropical forest vulnerability to drought. *New Phytologist*, **235** (3), 1005–1017. https://doi.org/10.1111/nph.18175

21. Michalak, A.M., E.J. Anderson, D. Beletsky, S. Boland, N.S. Bosch, T.B. Bridgeman, J.D. Chaffin, K. Cho, R. Confesor, I. Daloğlu, J.V. DePinto, M.A. Evans, G.L. Fahnenstiel, L. He, J.C. Ho, L. Jenkins, T.H. Johengen, K.C. Kuo, E. LaPorte, X. Liu, M.R. McWilliams, M.R. Moore, D.J. Posselt, R.P. Richards, D. Scavia, A.L. Steiner, E. Verhamme, D.M. Wright, and M.A. Zagorski, 2013: Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (16), 6448–6452. https://doi.org/10.1073/pnas.1216006110

22. Guiterman, C.H., R.M. Gregg, L.A.E. Marshall, J.J. Beckmann, P.J. van Mantgem, D.A. Falk, J.E. Keeley, A.C. Caprio, J.D. Coop, P.J. Fornwalt, C. Haffey, R.K. Hagmann, S.T. Jackson, A.M. Lynch, E.Q. Margolis, C. Marks, M.D. Meyer, H. Safford, A.D. Syphard, A. Taylor, C. Wilcox, D. Carril, C.A.F. Enquist, D. Huffman, J. Iniguez, N.A. Molinari, C. Restaino, and J.T. Stevens, 2022: Vegetation type conversion in the US Southwest: Frontline observations and management responses. *Fire Ecology*, **18** (1), 6. https://doi.org/10.1186/s42408-022-00131-w

23. Belote, R.T., C. Carroll, S. Martinuzzi, J. Michalak, J.W. Williams, M.A. Williamson, and G.H. Aplet, 2018: Assessing agreement among alternative climate change projections to inform conservation recommendations in the contiguous United States. *Scientific Reports*, **8** (1), 9441. https://doi.org/10.1038/s41598-018-27721-6

24. Michalak, J.L., J.C. Withey, J.J. Lawler, and M.J. Case, 2017: Future climate vulnerability—Evaluating multiple lines of evidence. *Frontiers in Ecology and the Environment*, **15** (7), 367–376. https://doi.org/10.1002/fee.1516

25. Heinze, C., T. Blenckner, H. Martins, D. Rusiecka, R. Döscher, M. Gehlen, N. Gruber, E. Holland, Ø. Hov, F. Joos, J.B.R. Matthews, R. Rødven, and S. Wilson, 2021: The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (9), e2008478118. https://doi.org/10.1073/pnas.2008478118

26. Selkoe, K.A., T. Blenckner, M.R. Caldwell, L.B. Crowder, A.L. Erickson, T.E. Essington, J.A. Estes, R.M. Fujita, B.S. Halpern, M.E. Hunsicker, C.V. Kappel, R.P. Kelly, J.N. Kittinger, P.S. Levin, J.M. Lynham, M.E. Mach, R.G. Martone, L.A. Mease, A.K. Salomon, J.F. Samhouri, C. Scarborough, A.C. Stier, C. White, and J. Zedler, 2015: Principles for managing marine ecosystems prone to tipping points. *Ecosystem Health and Sustainability*, **1** (5), 1–18. https://doi.org/10.1890/ehs14-0024.1

27. Hillebrand, H., I. Donohue, W.S. Harpole, D. Hodapp, M. Kucera, A.M. Lewandowska, J. Merder, J.M. Montoya, and J.A. Freund, 2020: Thresholds for ecological responses to global change do not emerge from empirical data. *Nature Ecology & Evolution*, **4** (11), 1502–1509. https://doi.org/10.1038/s41559-020-1256-9

28. Langer, M., T.S. von Deimling, S. Westermann, R. Rolph, R. Rutte, S. Antonova, V. Rachold, M. Schultz, A. Oehme, and G. Grosse, 2023: Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination. *Nature Communications*, **14** (1), 1721. https://doi.org/10.1038/s41467-023-37276-4

29. Miner, K.R., J. D'Andrilli, R. Mackelprang, A. Edwards, M.J. Malaska, M.P. Waldrop, and C.E. Miller, 2021: Emergent biogeochemical risks from Arctic permafrost degradation. *Nature Climate Change*, **11** (10), 809–819. https://doi.org/10.1038/s41558-021-01162-y

30. Schuur, E.A.G., B.W. Abbott, R. Commane, J. Ernakovich, E. Euskirchen, G. Hugelius, G. Grosse, M. Jones, C. Koven, V. Leshyk, D. Lawrence, M.M. Loranty, M. Mauritz, D. Olefeldt, S. Natali, H. Rodenhizer, V. Salmon, C. Schädel, J. Strauss, C. Treat, and M. Turetsky, 2022: Permafrost and climate change: Carbon cycle feedbacks from the warming Arctic. *Annual Review of Environment and Resources*, **47** (1), 343–371. https://doi.org/10.1146/annurev-environ-012220-011847

31. Ratajczak, Z., S.R. Carpenter, A.R. Ives, C.J. Kucharik, T. Ramiadantsoa, M.A. Stegner, J.W. Williams, J. Zhang, and M.G. Turner, 2018: Abrupt change in ecological systems: Inference and diagnosis. *Trends in Ecology & Evolution*, **33** (7), 513–526. https://doi.org/10.1016/j.tree.2018.04.013

32. Marshall, L.A. and D.A. Falk, 2020: Demographic trends in community functional tolerance reflect tree responses to climate and altered fire regimes. *Ecological Applications*, **30** (8), e02197. https://doi.org/10.1002/eap.2197

33. Hughes, T.P., J.T. Kerry, A.H. Baird, S.R. Connolly, T.J. Chase, A. Dietzel, T. Hill, A.S. Hoey, M.O. Hoogenboom, M. Jacobson, A. Kerswell, J.S. Madin, A. Mieog, A.S. Paley, M.S. Pratchett, G. Torda, and R.M. Woods, 2019: Global warming impairs stock–recruitment dynamics of corals. *Nature*, **568** (7752), 387–390. https://doi.org/10.1038/s41586-019-1081-y

34. Hughes, T.P., J.T. Kerry, A.H. Baird, S.R. Connolly, A. Dietzel, C.M. Eakin, S.F. Heron, A.S. Hoey, M.O. Hoogenboom, G. Liu, M.J. McWilliam, R.J. Pears, M.S. Pratchett, W.J. Skirving, J.S. Stella, and G. Torda, 2018: Global warming transforms coral reef assemblages. *Nature*, **556** (7702), 492–496. https://doi.org/10.1038/s41586-018-0041-2

35. Williams, J.W., A. Ordonez, and J.-C. Svenning, 2021: A unifying framework for studying and managing climate-driven rates of ecological change. *Nature Ecology & Evolution*, **5** (1), 17–26. https://doi.org/10.1038/s41559-020-01344-5

36. Turner, M.G., W.J. Calder, G.S. Cumming, T.P. Hughes, A. Jentsch, S.L. LaDeau, T.M. Lenton, B.N. Shuman, M.R. Turetsky, Z. Ratajczak, J.W. Williams, A.P. Williams, and S.R. Carpenter, 2020: Climate change, ecosystems and abrupt change: Science priorities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190105. https://doi.org/10.1098/rstb.2019.0105

37. Svejcar, L.N., J.D. Kerby, T.J. Svejcar, B. Mackey, C.S. Boyd, O.W. Baughman, M.D. Madsen, and K.W. Davies, 2023: Plant recruitment in drylands varies by site, year, and seeding technique. *Restoration Ecology*, **31** (2), e13750. https://doi.org/10.1111/rec.13750

38. Foley, M.M., R.G. Martone, M.D. Fox, C.V. Kappel, L.A. Mease, A.L. Erickson, B.S. Halpern, K.A. Selkoe, P. Taylor, and C. Scarborough, 2015: Using ecological thresholds to inform resource management: Current options and future possibilities. *Frontiers in Marine Science*, **2**, 95. https://doi.org/10.3389/fmars.2015.00095

39. Johnstone, J.F., C.D. Allen, J.F. Franklin, L.E. Frelich, B.J. Harvey, P.E. Higuera, M.C. Mack, R.K. Meentemeyer, M.R. Metz, G.L.W. Perry, T. Schoennagel, and M.G. Turner, 2016: Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment*, **14** (7), 369–378. https://doi.org/10.1002/fee.1311

40. Hutchison, C., D. Gravel, F. Guichard, and C. Potvin, 2018: Effect of diversity on growth, mortality, and loss of resilience to extreme climate events in a tropical planted forest experiment. *Scientific Reports*, **8** (1), 15443. https://doi.org/10.1038/s41598-018-33670-x

41. Isbell, F., D. Craven, J. Connolly, M. Loreau, B. Schmid, C. Beierkuhnlein, T.M. Bezemer, C. Bonin, H. Bruelheide, E. de Luca, A. Ebeling, J.N. Griffin, Q. Guo, Y. Hautier, A. Hector, A. Jentsch, J. Kreyling, V. Lanta, P. Manning, S.T. Meyer, A.S. Mori, S. Naeem, P.A. Niklaus, H.W. Polley, P.B. Reich, C. Roscher, E.W. Seabloom, M.D. Smith, M.P. Thakur, D. Tilman, B.F. Tracy, W.H. van der Putten, J. van Ruijven, A. Weigelt, W.W. Weisser, B. Wilsey, and N. Eisenhauer, 2015: Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature*, **526** (7574), 574–577. https://doi.org/10.1038/nature15374

42. Farr, E.R., M.R. Johnson, M.W. Nelson, J.A. Hare, W.E. Morrison, M.D. Lettrich, B. Vogt, C. Meaney, U.A. Howson, P.J. Auster, F.A. Borsuk, D.C. Brady, M.J. Cashman, P. Colarusso, J.H. Grabowski, J.P. Hawkes, R. Mercaldo-Allen, D.B. Packer, and D.K. Stevenson, 2021: An assessment of marine, estuarine, and riverine habitat vulnerability to climate change in the Northeast U.S. *PLoS ONE*, **16** (12), e0260654. https://doi.org/10.1371/journal.pone.0260654

43. Osland, M.J., R.H. Day, and T.C. Michot, 2020: Frequency of extreme freeze events controls the distribution and structure of black mangroves (*Avicennia germinans*) near their northern range limit in coastal Louisiana. *Diversity and Distributions*, **26** (10), 1366–1382. https://doi.org/10.1111/ddi.13119

44. Osland, M.J., A.R. Hughes, A.R. Armitage, S.B. Scyphers, J. Cebrian, S.H. Swinea, C.C. Shepard, M.S. Allen, L.C. Feher, J.A. Nelson, C.L. O'Brien, Colt R. Sanspree, D.L. Smee, C.M. Snyder, A.P. Stetter, Philip W. Stevens, K.M. Swanson, L.H. Williams, Janell M. Brush, J. Marchionno, and R. Bardou, 2022: The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: Current understanding, knowledge gaps, and emerging research needs. *Global Change Biology*, **28** (10), 3163–3187. https://doi.org/10.1111/gcb.16111

45. Osland, M.J., P.W. Stevens, M.M. Lamont, R.C. Brusca, K.M. Hart, J.H. Waddle, C.A. Langtimm, C.M. Williams, B.D. Keim, A.J. Terando, E.A. Reyier, K.E. Marshall, M.E. Loik, R.E. Boucek, A.B. Lewis, and J.A. Seminoff, 2021: Tropicalization of temperate ecosystems in North America: The northward range expansion of tropical organisms in response to warming winter temperatures. *Global Change Biology*, **27** (13), 3009–3034. https://doi.org/10.1111/gcb.15563

46. Ury, E.A., X. Yang, J.P. Wright, and E.S. Bernhardt, 2021: Rapid deforestation of a coastal landscape driven by sea-level rise and extreme events. *Ecological Applications*, **31** (5), e02339. https://doi.org/10.1002/eap.2339

47. Barnard, P.L., J.E. Dugan, H.M. Page, N.J. Wood, J.A.F. Hart, D.R. Cayan, L.H. Erikson, D.M. Hubbard, M.R. Myers, J.M. Melack, and S.F. Iacobellis, 2021: Multiple climate change-driven tipping points for coastal systems. *Scientific Reports*, **11** (1), 15560. https://doi.org/10.1038/s41598-021-94942-7

48. Malhi, Y., C. Girardin, D.B. Metcalfe, C.E. Doughty, L.E.O.C. Aragão, S.W. Rifai, I. Oliveras, A. Shenkin, J. Aguirre-Gutiérrez, C.A.L. Dahlsjö, T. Riutta, E. Berenguer, S. Moore, W.H. Huasco, N. Salinas, A.C.L. da Costa, L.P. Bentley, S. Adu-Bredu, T.R. Marthews, P. Meir, and O.L. Phillips, 2021: The Global Ecosystems Monitoring network: Monitoring ecosystem productivity and carbon cycling across the tropics. *Biological Conservation*, **253**, 108889. https://doi.org/10.1016/j.biocon.2020.108889

49. Scheffer, M., S.R. Carpenter, V. Dakos, and E.H. van Nes, 2015: Generic indicators of ecological resilience: Inferring the chance of a critical transition. *Annual Review of Ecology, Evolution, and Systematics*, **46** (1), 145–167. https://doi.org/10.1146/annurev-ecolsys-112414-054242

50. Jones, J.A. and C.T. Driscoll, 2022: Long-term ecological research on ecosystem responses to climate change. *BioScience*, **72** (9), 814–826. https://doi.org/10.1093/biosci/biac021

51. Unger, S., M. Rollins, A. Tietz, and H. Dumais, 2021: iNaturalist as an engaging tool for identifying organisms in outdoor activities. *Journal of Biological Education*, **55** (5), 537–547. https://doi.org/10.1080/00219266.2020.1739114

52. Crimmins, T., E. Denny, E. Posthumus, A. Rosemartin, R. Croll, M. Montano, and H. Panci, 2022: Science and management advancements made possible by the USA National Phenology network's nature's notebook platform. *BioScience*, **72** (9), 908–920. https://doi.org/10.1093/biosci/biac061

53. Danielsen, F., H. Eicken, M. Funder, N. Johnson, O. Lee, I. Theilade, D. Argyriou, and N.D. Burgess, 2022: Community monitoring of natural resource systems and the environment. *Annual Review of Environment and Resources*, **47** (1), 637–670. https://doi.org/10.1146/annurev-environ-012220-022325

54. Pearson, J., G. Jackson, and K.E. McNamara, 2023: Climate-driven losses to Indigenous and local knowledge and cultural heritage. *The Anthropocene Review*, **10** (2), 343–366. https://doi.org/10.1177/20530196211005482

55. McKinley, D.C., A.J. Miller-Rushing, H.L. Ballard, R. Bonney, H. Brown, S.C. Cook-Patton, D.M. Evans, R.A. French, J.K. Parrish, T.B. Phillips, S.F. Ryan, L.A. Shanley, J.L. Shirk, K.F. Stepenuck, J.F. Weltzin, A. Wiggins, O.D. Boyle, R.D. Briggs, S.F. Chapin, D.A. Hewitt, P.W. Preuss, and M.A. Soukup, 2017: Citizen science can improve conservation science, natural resource management, and environmental protection. *Biological Conservation*, **208**, 15–28. https://doi.org/10.1016/j.biocon.2016.05.015

56. Currie, D.J. and S. Venne, 2017: Climate change is not a major driver of shifts in the geographical distributions of North American birds. *Global Ecology and Biogeography*, **26** (3), 333–346. https://doi.org/10.1111/geb.12538

57. Valle, D., P. Albuquerque, Q. Zhao, A. Barberan, and R.J. Fletcher Jr., 2018: Extending the Latent Dirichlet Allocation model to presence/absence data: A case study on North American breeding birds and biogeographical shifts expected from climate change. *Global Change Biology*, **24** (11), 5560–5572. https://doi.org/10.1111/gcb.14412

58. Wang, J., D. Liu, P. Ciais, and J. Peñuelas, 2022: Decreasing rainfall frequency contributes to earlier leaf onset in northern ecosystems. *Nature Climate Change*, **12**, 386–392. https://doi.org/10.1038/s41558-022-01285-w

59. Nolan, C., J.T. Overpeck, J.R.M. Allen, P.M. Anderson, J.L. Betancourt, H.A. Binney, S. Brewer, M.B. Bush, B.M. Chase, R. Cheddadi, M. Djamali, J. Dodson, M.E. Edwards, W.D. Gosling, S. Haberle, S.C. Hotchkiss, B. Huntley, S.J. Ivory, A.P. Kershaw, S.-H. Kim, C. Latorre, M. Leydet, A.-M. Lézine, K.-B. Liu, Y. Liu, A.V. Lozhkin, M.S. McGlone, R.A. Marchant, A. Momohara, P.I. Moreno, S. Müller, B.L. Otto-Bliesner, C. Shen, J. Stevenson, H. Takahara, P.E. Tarasov, J. Tipton, A. Vincens, C. Weng, Q. Xu, Z. Zheng, and S.T. Jackson, 2018: Past and future global transformation of terrestrial ecosystems under climate change. *Science*, **361** (6405), 920–923. https://doi.org/10.1126/science.aan5360

60. Chambers, J.C., C.R. Allen, and S.A. Cushman, 2019: Operationalizing ecological resilience concepts for managing species and ecosystems at risk. *Frontiers in Ecology and Evolution*, **7**, 241. https://doi.org/10.3389/fevo.2019.00241

61. França, F.M., C.E. Benkwitt, G. Peralta, J.P.W. Robinson, N.A.J. Graham, J.M. Tylianakis, E. Berenguer, A.C. Lees, J. Ferreira, J. Louzada, and J. Barlow, 2020: Climatic and local stressor interactions threaten tropical forests and coral reefs. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190116. https://doi.org/10.1098/rstb.2019.0116

62. Schuurman, G.W., C.H. Hoffman, D.N. Cole, D.J. Lawrence, J.M. Morton, D.R. Magness, A.E. Cravens, S. Covington, R. O'Malley, and N.A. Fisichelli, 2020: Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager. Natural Resource Report. NPS/NRSS/CCRP/NRR—2020/2213. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://doi.org/10.36967/nrr-2283597

63. Akamani, K., 2016: Adaptive water governance: Integrating the human dimensions into water resource governance. *Journal of Contemporary Water Research & Education*, **158** (1), 2–18. https://doi.org/10.1111/j.1936-704x.2016.03215.x

64. Pahl-Wostl, C., 2019: The role of governance modes and meta-governance in the transformation towards sustainable water governance. *Environmental Science & Policy*, **91**, 6–16. https://doi.org/10.1016/j.envsci.2018.10.008

65. Pahl-Wostl, C., C. Knieper, E. Lukat, F. Meergans, M. Schoderer, N. Schütze, D. Schweigatz, I. Dombrowsky, A. Lenschow, U. Stein, A. Thiel, J. Tröltzsch, and R. Vidaurre, 2020: Enhancing the capacity of water governance to deal with complex management challenges: A framework of analysis. *Environmental Science & Policy*, **107**, 23–35. https://doi.org/10.1016/j.envsci.2020.02.011

66. Akamani, K., 2021: An ecosystem-based approach to climate-smart agriculture with some considerations for social equity. *Agronomy*, **11** (8), 1564. https://doi.org/10.3390/agronomy11081564

67. Hörl, J., K. Keller, and R. Yousefpour, 2020: Reviewing the performance of adaptive forest management strategies with robustness analysis. *Forest Policy and Economics*, **119**, 102289. https://doi.org/10.1016/j.forpol.2020.102289

68. Akamani, K., 2020: Integrating deep ecology and adaptive governance for sustainable development: Implications for protected areas management. *Sustainability*, **12** (14), 5757. https://doi.org/10.3390/su12145757

69. Dietz, T., 2013: Bringing values and deliberation to science communication. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (Supplement_3), 14081–14087. https://doi.org/10.1073/pnas.1212740110

70. Romsdahl, R., G. Blue, and A. Kirilenko, 2018: Action on climate change requires deliberative framing at local governance level. *Climatic Change*, **149** (3), 277–287. https://doi.org/10.1007/s10584-018-2240-0

71. Magness, D.R., L. Hoang, R.T. Belote, J. Brennan, W. Carr, F. Stuart Chapin, III, K. Clifford, W. Morrison, J.M. Morton, and H.R. Sofaer, 2022: Management foundations for navigating ecological transformation by resisting, accepting, or directing social–ecological change. *BioScience*, **72** (1), 30–44. https://doi.org/10.1093/biosci/biab083

72. Lynch, A.J., L.M. Thompson, J.M. Morton, E.A. Beever, M. Clifford, D. Limpinsel, R.T. Magill, D.R. Magness, T.A. Melvin, R.A. Newman, M.T. Porath, F.J. Rahel, J.H. Reynolds, G.W. Schuurman, S.A. Sethi, and J.L. Wilkening, 2022: RAD adaptive management for transforming ecosystems. *BioScience*, **72** (1), 45–56. https://doi.org/10.1093/biosci/biab091

73. Magness, D.R., E. Wagener, E. Yurcich, R. Mollnow, D. Granfors, and J.L. Wilkening, 2022: A multi-scale blueprint for building the decision context to implement climate change adaptation on national wildlife refuges in the United States. *Earth*, **3** (1), 136–156. https://doi.org/10.3390/earth3010011

74. West, J.M., C.A. Courtney, A.T. Hamilton, B.A. Parker, D.A. Gibbs, P. Bradley, and S.H. Julius, 2018: Adaptation design tool for climate-smart management of coral reefs and other natural resources. *Environmental Management*, **62** (4), 644–664. https://doi.org/10.1007/s00267-018-1065-y

75. West, J.M., C.A. Courtney, A.T. Hamilton, B.A. Parker, S.H. Julius, J. Hoffman, K.H. Koltes, and P. MacGowan, 2017: Climate-smart design for ecosystem management: A test application for coral reefs. *Environmental management*, **59** (1), 102–117. https://doi.org/10.1007/s00267-016-0774-3

76. Caro, T., Z. Rowe, J. Berger, P. Wholey, and A. Dobson, 2022: An inconvenient misconception: Climate change is not the principal driver of biodiversity loss. *Conservation Letters*, **15** (3), e12868. https://doi.org/10.1111/conl.12868

77. Jaureguiberry, P., N. Titeux, M. Wiemers, D.E. Bowler, L. Coscieme, A.S. Golden, C.A. Guerra, U. Jacob, Y. Takahashi, J. Settele, S. Díaz, Z. Molnár, and A. Purvis, 2022: The direct drivers of recent global anthropogenic biodiversity loss. *Science Advances*, **8** (45), 9982. https://doi.org/10.1126/sciadv.abm9982

78. Pansch, C., M. Scotti, F.R. Barboza, B. Al-Janabi, J. Brakel, E. Briski, B. Bucholz, M. Franz, M. Ito, F. Paiva, M. Saha, Y. Sawall, F. Weinberger, and M. Wahl, 2018: Heat waves and their significance for a temperate benthic community: A near-natural experimental approach. *Global Change Biology*, **24** (9), 4357–4367. https://doi.org/10.1111/gcb.14282

79. Peterson Williams, M.J., B. Robbins Gisclair, E. Cerny-Chipman, M. LeVine, and T. Peterson, 2022: The heat is on: Gulf of Alaska Pacific cod and climate-ready fisheries. *ICES Journal of Marine Science*, **79** (2), 573–583. https://doi.org/10.1093/icesjms/fsab032

80. Richards, R.A. and M. Hunter, 2021: Northern shrimp *Pandalus borealis* population collapse linked to climate-driven shifts in predator distribution. *PLoS ONE*, **16** (7), e0253914. https://doi.org/10.1371/journal.pone.0253914

81. Carlson, R.R., S.A. Foo, and G.P. Asner, 2019: Land use impacts on coral reef health: A ridge-to-reef perspective. *Frontiers in Marine Science*, **6**, 562. https://doi.org/10.3389/fmars.2019.00562

82. Evensen, N.R., Y.-M. Bozec, P.J. Edmunds, and P.J. Mumby, 2021: Scaling the effects of ocean acidification on coral growth and coral–coral competition on coral community recovery. *PeerJ*, **9**, e11608. https://doi.org/10.7717/peerj.11608

83. Johnson, M.D., J.J. Scott, M. Leray, N. Lucey, L.M.R. Bravo, W.L. Wied, and A.H. Altieri, 2021: Rapid ecosystem-scale consequences of acute deoxygenation on a Caribbean coral reef. *Nature Communications*, **12** (1), 4522. https://doi.org/10.1038/s41467-021-24777-3

84. Magel, J.M.T., J.H.R. Burns, R.D. Gates, and J.K. Baum, 2019: Effects of bleaching-associated mass coral mortality on reef structural complexity across a gradient of local disturbance. *Scientific Reports*, **9** (1), 2512. https://doi.org/10.1038/s41598-018-37713-1

85. Sampaio, E., C. Santos, I.C. Rosa, V. Ferreira, H.-O. Pörtner, C.M. Duarte, L.A. Levin, and R. Rosa, 2021: Impacts of hypoxic events surpass those of future ocean warming and acidification. *Nature Ecology & Evolution*, **5** (3), 311–321. https://doi.org/10.1038/s41559-020-01370-3

86. Smale, D.A., T. Wernberg, E.C.J. Oliver, M. Thomsen, B.P. Harvey, S.C. Straub, M.T. Burrows, L.V. Alexander, J.A. Benthuysen, M.G. Donat, M. Feng, A.J. Hobday, N.J. Holbrook, S.E. Perkins-Kirkpatrick, H.A. Scannell, A. Sen Gupta, B.L. Payne, and P.J. Moore, 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9** (4), 306–312. https://doi.org/10.1038/s41558-019-0412-1

87. Kelly, L.T., K.M. Giljohann, A. Duane, N. Aquilué, S. Archibald, E. Batllori, A.F. Bennett, S.T. Buckland, Q. Canelles, M.F. Clarke, M.-J. Fortin, V. Hermoso, S. Herrando, R.E. Keane, F.K. Lake, M.A. McCarthy, A. Morán-Ordóñez, C.L. Parr, J.G. Pausas, T.D. Penman, A. Regos, L. Rumpff, J.L. Santos, A.L. Smith, A.D. Syphard, M.W. Tingley, and L. Brotons, 2020: Fire and biodiversity in the Anthropocene. *Science*, **370** (6519), 0355. https://doi.org/10.1126/science.abb0355

88. Jager, H.I., J.W. Long, R.L. Malison, B.P. Murphy, A. Rust, L.G.M. Silva, R. Sollmann, Z.L. Steel, M.D. Bowen, J.B. Dunham, J.L. Ebersole, and R.L. Flitcroft, 2021: Resilience of terrestrial and aquatic fauna to historical and future wildfire regimes in western North America. *Ecology and Evolution*, **11** (18), 12259–12284. https://doi.org/10.1002/ece3.8026

89. Jones, N.P., L. Kabay, K. Semon Lunz, and D.S. Gilliam, 2021: Temperature stress and disease drives the extirpation of the threatened pillar coral, *Dendrogyra cylindrus*, in southeast Florida. *Scientific Reports*, **11** (1), 14113. https://doi.org/10.1038/s41598-021-93111-0

90. Cohen, J.M., M.J. Lajeunesse, and J.R. Rohr, 2018: A global synthesis of animal phenological responses to climate change. *Nature Climate Change*, **8** (3), 224–228. https://doi.org/10.1038/s41558-018-0067-3

91. Franklin, K.A., M.A.C. Nicoll, S.J. Butler, K. Norris, N. Ratcliffe, S. Nakagawa, and J.A. Gill, 2022: Individual repeatability of avian migration phenology: A systematic review and meta-analysis. *Journal of Animal Ecology*, **91** (7), 1416–1430. https://doi.org/10.1111/1365-2656.13697

92. Inouye, D.W., 2022: Climate change and phenology. *WIREs Climate Change*, **13** (3), e764. https://doi.org/10.1002/wcc.764

93. Bai, H., D. Xiao, H. Zhang, F. Tao, and Y. Hu, 2019: Impact of warming climate, sowing date, and cultivar shift on rice phenology across China during 1981–2010. *International Journal of Biometeorology*, **63** (8), 1077–1089. https://doi.org/10.1007/s00484-019-01723-z

94. Liang, L., G.M. Henebry, L. Liu, X. Zhang, and L.-C. Hsu, 2021: Trends in land surface phenology across the conterminous United States (1982–2016) analyzed by NEON domains. *Ecological Applications*, **31** (5), e02323. https://doi.org/10.1002/eap.2323

95. Menzel, A., Y. Yuan, M. Matiu, T. Sparks, H. Scheifinger, R. Gehrig, and N. Estrella, 2020: Climate change fingerprints in recent European plant phenology. *Global Change Biology*, **26** (4), 2599–2612. https://doi.org/10.1111/gcb.15000

96. Song, Y., C.J. Zajic, T. Hwang, C.R. Hakkenberg, and K. Zhu, 2021: Widespread mismatch between phenology and climate in human-dominated landscapes. *AGU Advances*, **2** (4), e2021AV000431. https://doi.org/10.1029/2021av000431

97. Thornton, P.K., P.J. Ericksen, M. Herrero, and A.J. Challinor, 2014: Climate variability and vulnerability to climate change: A review. *Global Change Biology*, **20** (11), 3313–3328. https://doi.org/10.1111/gcb.12581

98. Anderegg, W.R.L., J.T. Abatzoglou, L.D.L. Anderegg, L. Bielory, P.L. Kinney, and L. Ziska, 2021: Anthropogenic climate change is worsening North American pollen seasons. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (7), e2013284118. https://doi.org/10.1073/pnas.2013284118

99. Deutsch, C.A., J.J. Tewksbury, M. Tigchelaar, D.S. Battisti, S.C. Merrill, R.B. Huey, and R.L. Naylor, 2018: Increase in crop losses to insect pests in a warming climate. *Science*, **361** (6405), 916–919. https://doi.org/10.1126/science.aat3466

100. Schneider, L., M. Rebetez, and S. Rasmann, 2022: The effect of climate change on invasive crop pests across biomes. *Current Opinion in Insect Science*, **50**, 100895. https://doi.org/10.1016/j.cois.2022.100895

101. Li, D., B.J. Stucky, B. Baiser, and R. Guralnick, 2022: Urbanization delays plant leaf senescence and extends growing season length in cold but not in warm areas of the Northern Hemisphere. *Global Ecology and Biogeography*, **31** (2), 308–320. https://doi.org/10.1111/geb.13429

102. Li, D., B.J. Stucky, J. Deck, B. Baiser, and R.P. Guralnick, 2019: The effect of urbanization on plant phenology depends on regional temperature. *Nature Ecology & Evolution*, **3** (12), 1661–1667. https://doi.org/10.1038/s41559-019-1004-1

103. Kharouba, H.M., J. Ehrlén, A. Gelman, K. Bolmgren, J.M. Allen, S.E. Travers, and E.M. Wolkovich, 2018: Global shifts in the phenological synchrony of species interactions over recent decades. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (20), 5211–5216. https://doi.org/10.1073/pnas.1714511115

104. Visser, M.E. and P. Gienapp, 2019: Evolutionary and demographic consequences of phenological mismatches. *Nature Ecology & Evolution*, **3** (6), 879–885. https://doi.org/10.1038/s41559-019-0880-8

105. Heberling, J.M., C. McDonough MacKenzie, J.D. Fridley, S. Kalisz, and R.B. Primack, 2019: Phenological mismatch with trees reduces wildflower carbon budgets. *Ecology Letters*, **22** (4), 616–623. https://doi.org/10.1111/ele.13224

106. Richardson, A.D., K. Hufkens, T. Milliman, D.M. Aubrecht, M.E. Furze, B. Seyednasrollah, M.B. Krassovski, J.M. Latimer, W.R. Nettles, R.R. Heiderman, J.M. Warren, and P.J. Hanson, 2018: Ecosystem warming extends vegetation activity but heightens vulnerability to cold temperatures. *Nature*, **560** (7718), 368–371. https://doi.org/10.1038/s41586-018-0399-1

107. Lambers, J.H.R., A.F. Cannistra, A. John, E. Lia, R.D. Manzanedo, M. Sethi, J. Sevigny, E.J. Theobald, and J.K. Waugh, 2021: Climate change impacts on natural icons: Do phenological shifts threaten the relationship between peak wildflowers and visitor satisfaction? *Climate Change Ecology*, **2**, 100008. https://doi.org/10.1016/j.ecochg.2021.100008

108. Ojea, E., S.E. Lester, and D. Salgueiro-Otero, 2020: Adaptation of fishing communities to climate-driven shifts in target species. *One Earth*, **2** (6), 544–556. https://doi.org/10.1016/j.oneear.2020.05.012

109. Fredston, A., M. Pinsky, R.L. Selden, C. Szuwalski, J.T. Thorson, S.D. Gaines, and B.S. Halpern, 2021: Range edges of North American marine species are tracking temperature over decades. *Global Change Biology*, **27** (13), 3145–3156. https://doi.org/10.1111/gcb.15614

110. MacLean, S.A. and S.R. Beissinger, 2017: Species' traits as predictors of range shifts under contemporary climate change: A review and meta-analysis. *Global Change Biology*, **23** (10), 4094–4105. https://doi.org/10.1111/gcb.13736

111. Pacifici, M., P. Visconti, S.H.M. Butchart, J.E.M. Watson, Francesca M. Cassola, and C. Rondinini, 2017: Species' traits influenced their response to recent climate change. *Nature Climate Change*, **7** (3), 205–208. https://doi.org/10.1038/nclimate3223

112. Lenoir, J., R. Bertrand, L. Comte, L. Bourgeaud, T. Hattab, J. Murienne, and G. Grenouillet, 2020: Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, **4** (8), 1044–1059. https://doi.org/10.1038/s41559-020-1198-2

113. Freeman, B.G., J.A. Lee-Yaw, J.M. Sunday, and A.L. Hargreaves, 2018: Expanding, shifting and shrinking: The impact of global warming on species' elevational distributions. *Global Ecology and Biogeography*, **27** (11), 1268–1276. https://doi.org/10.1111/geb.12774

114. Graves, T.A., W.M. Janousek, S.M. Gaulke, A.C. Nicholas, D.A. Keinath, C.M. Bell, S. Cannings, R.G. Hatfield, J.M. Heron, J.B. Koch, H.L. Loffland, L.L. Richardson, A.T. Rohde, J. Rykken, J.P. Strange, L.M. Tronstad, and C.S. Sheffield, 2020: Western bumble bee: Declines in the continental United States and range-wide information gaps. *Ecosphere*, **11** (6), e03141. https://doi.org/10.1002/ecs2.3141

115. Lehmann, P., T. Ammunét, M. Barton, A. Battisti, S.D. Eigenbrode, J.U. Jepsen, G. Kalinkat, S. Neuvonen, P. Niemelä, J.S. Terblanche, B. Økland, and C. Björkman, 2020: Complex responses of global insect pests to climate warming. *Frontiers in Ecology and the Environment*, **18** (3), 141–150. https://doi.org/10.1002/fee.2160

116. Wagner, D.L., E.M. Grames, M.L. Forister, M.R. Berenbaum, and D. Stopak, 2021: Insect decline in the Anthropocene: Death by a thousand cuts. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2023989118. https://doi.org/10.1073/pnas.2023989118

117. Choi, F., T. Gouhier, F. Lima, G. Rilov, R. Seabra, and B. Helmuth, 2019: Mapping physiology: Biophysical mechanisms define scales of climate change impacts. *Conservation Physiology*, **7** (1), 028. https://doi.org/10.1093/conphys/coz028

118. Forister, M.L., A.C. McCall, N.J. Sanders, J.A. Fordyce, J.H. Thorne, J. O'Brien, D.P. Waetjen, and A.M. Shapiro, 2010: Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity. *Proceedings of the National Academy of Sciences of the United States of America*, **107** (5), 2088–2092. https://doi.org/10.1073/pnas.0909686107

119. Kroeker, K.J., E. Sanford, J.M. Rose, C.A. Blanchette, F. Chan, F.P. Chavez, B. Gaylord, B. Helmuth, T.M. Hill, G.E. Hofmann, M.A. McManus, B.A. Menge, K.J. Nielsen, P.T. Raimondi, A.D. Russell, and L. Washburn, 2016: Interacting environmental mosaics drive geographic variation in mussel performance and predation vulnerability. *Ecology Letters*, **19** (7), 771–779. https://doi.org/10.1111/ele.12613

120. McLaughlin, B.C., D.D. Ackerly, P.Z. Klos, J. Natali, T.E. Dawson, and S.E. Thompson, 2017: Hydrologic refugia, plants, and climate change. *Global Change Biology*, **23** (8), 2941–2961. https://doi.org/10.1111/gcb.13629

121. Morelli, T.L., C.W. Barrows, A.R. Ramirez, J.M. Cartwright, D.D. Ackerly, T.D. Eaves, J.L. Ebersole, M.A. Krawchuk, B.H. Letcher, M.F. Mahalovich, G.W. Meigs, J.L. Michalak, C.I. Millar, R.M. Quiñones, D. Stralberg, and J.H. Thorne, 2020: Climate-change refugia: Biodiversity in the slow lane. *Frontiers in Ecology and the Environment*, **18** (5), 228–234. https://doi.org/10.1002/fee.2189

122. Salois, S.L., T.C. Gouhier, B. Helmuth, F. Choi, R. Seabra, and F.P. Lima, 2022: Coastal upwelling generates cryptic temperature refugia. *Scientific Reports*, **12** (1), 19313. https://doi.org/10.1038/s41598-022-23717-5

123. Stralberg, D., C. Carroll, and S.E. Nielsen, 2020: Toward a climate-informed North American protected areas network: Incorporating climate-change refugia and corridors in conservation planning. *Conservation Letters*, **13** (4), e12712. https://doi.org/10.1111/conl.12712

124. Hannah, L., L. Flint, A.D. Syphard, M.A. Moritz, L.B. Buckley, and I.M. McCullough, 2014: Fine-grain modeling of species' response to climate change: Holdouts, stepping-stones, and microrefugia. *Trends in Ecology & Evolution*, **29** (7), 390–397. https://doi.org/10.1016/j.tree.2014.04.006

125. Peach, M.A., J.B. Cohen, J.L. Frair, B. Zuckerberg, P. Sullivan, W.F. Porter, and C. Lang, 2019: Value of protected areas to avian persistence across 20 years of climate and land-use change. *Conservation Biology*, **33** (2), 423–433. https://doi.org/10.1111/cobi.13205

126. Dixon, A.M., P.M. Forster, S.F. Heron, A.M.K. Stoner, and M. Beger, 2022: Future loss of local-scale thermal refugia in coral reef ecosystems. *PLoS Climate*, **1** (2), e0000004. https://doi.org/10.1371/journal.pclm.0000004

127. Ebersole, J.L., R.M. Quiñones, S. Clements, and B.H. Letcher, 2020: Managing climate refugia for freshwater fishes under an expanding human footprint. *Frontiers in Ecology and the Environment*, **18** (5), 271–280. https://doi.org/10.1002/fee.2206

128. Storlazzi, C.D., O.M. Cheriton, R. van Hooidonk, Z. Zhao, and R. Brainard, 2020: Internal tides can provide thermal refugia that will buffer some coral reefs from future global warming. *Scientific Reports*, **10** (1), 13435. https://doi.org/10.1038/s41598-020-70372-9

129. Tang, C.Q., T. Matsui, H. Ohashi, Y.-F. Dong, A. Momohara, S. Herrando-Moraira, S. Qian, Y. Yang, M. Ohsawa, H.T. Luu, P.J. Grote, P.V. Krestov, L. Ben, M. Werger, K. Robertson, C. Hobohm, C.-Y. Wang, M.-C. Peng, X. Chen, H.-C. Wang, W.-H. Su, R. Zhou, S. Li, L.-Y. He, K. Yan, M.-Y. Zhu, J. Hu, R.-H. Yang, W.-J. Li, M. Tomita, Z.-L. Wu, H.-Z. Yan, G.-F. Zhang, H. He, S.-R. Yi, H. Gong, K. Song, D. Song, X.-S. Li, Z.-Y. Zhang, P.-B. Han, L.-Q. Shen, D.-S. Huang, K. Luo, and J. López-Pujol, 2018: Identifying long-term stable refugia for relict plant species in East Asia. *Nature Communications*, **9** (1), 4488. https://doi.org/10.1038/s41467-018-06837-3

130. Morelli, T.L., C. Daly, S.Z. Dobrowski, D.M. Dulen, J.L. Ebersole, S.T. Jackson, J.D. Lundquist, C.I. Millar, S.P. Maher, W.B. Monahan, K.R. Nydick, K.T. Redmond, S.C. Sawyer, S. Stock, and S.R. Beissinger, 2016: Managing climate change refugia for climate adaptation. *PLoS ONE*, **11** (8), e0159909. https://doi.org/10.1371/journal.pone.0159909

131. Madliger, C.L., C.E. Franklin, O.P. Love, and S.J. Cooke, Eds., 2020: *Conservation Physiology: Applications for Wildlife Conservation and Management*. Oxford University Press. https://doi.org/10.1093/oso/9780198843610.001.0001

132. Royer-Tardif, S., L. Boisvert-Marsh, J. Godbout, N. Isabel, and I. Aubin, 2021: Finding common ground: Toward comparable indicators of adaptive capacity of tree species to a changing climate. *Ecology and Evolution*, **11** (19), 13081–13100. https://doi.org/10.1002/ece3.8024

133. Grose, S.O., L. Pendleton, A. Leathers, A. Cornish, and S. Waitai, 2020: Climate change will re-draw the map for marine megafauna and the people who depend on them. *Frontiers in Marine Science*, **7**, 547. https://doi.org/10.3389/fmars.2020.00547

134. Penn, J.L. and C. Deutsch, 2022: Avoiding ocean mass extinction from climate warming. *Science*, **376** (6592), 524–526. https://doi.org/10.1126/science.abe9039

135. Christiansen, F., S.M. Dawson, J.W. Durban, H. Fearnbach, C.A. Miller, L. Bejder, M. Uhart, M. Sironi, P. Corkeron, W. Rayment, E. Leunissen, E. Haria, R. Ward, H.A. Warick, I. Kerr, M.S. Lynn, H.M. Pettis, and M.J. Moore, 2020: Population comparison of right whale body condition reveals poor state of the North Atlantic right whale. *Marine Ecology Progress Series*, **640**, 1–16. https://doi.org/10.3354/meps13299

136. Pimiento, C., F. Leprieur, D. Silvestro, J.S. Lefcheck, C. Albouy, D.B. Rasher, M. Davis, J.-C. Svenning, and J.N. Griffin, 2020: Functional diversity of marine megafauna in the Anthropocene. *Science Advances*, **6** (16), 7650. https://doi.org/10.1126/sciadv.aay7650

137. Pershing, A.J. and K. Stamieszkin, 2020: The North Atlantic ecosystem, from plankton to whales. *Annual Review of Marine Science*, **12**, 339–359. https://doi.org/10.1146/annurev-marine-010419-010752

138. Sorochan, K.A., S. Plourde, M.F. Baumgartner, and C.L. Johnson, 2021: Availability, supply, and aggregation of prey (*Calanus* spp.) in foraging areas of the North Atlantic right whale (*Eubalaena glacialis*). *ICES Journal of Marine Science*, **78** (10), 3498–3520. https://doi.org/10.1093/icesjms/fsab200

139. Record, N.R., J.A. Runge, D.E. Pendleton, W.M. Balch, K.T.A. Davies, A.J. Pershing, C.L. Johnson, K. Stamieszkin, R. Ji, Z. Feng, S.D. Kraus, R.D. Kenney, C.A. Hudak, C.A. Mayo, C. Chen, J.E. Salisbury, and C.R.S. Thompson, 2019: Rapid climate-driven circulation changes threaten conservation of endangered North Atlantic right whales. *Oceanography*, **32** (2), 162–169. https://doi.org/10.5670/oceanog.2019.201

140. Stewart, J.D., J.W. Durban, A.R. Knowlton, M.S. Lynn, H. Fearnbach, J. Barbaro, W.L. Perryman, C.A. Miller, and M.J. Moore, 2021: Decreasing body lengths in North Atlantic right whales. *Current Biology*, **31** (14), 3174–3179. https://doi.org/10.1016/j.cub.2021.04.067

141. Bullen, C.D., A.A. Campos, E.J. Gregr, I. McKechnie, and K.M.A. Chan, 2021: The ghost of a giant—Six hypotheses for how an extinct megaherbivore structured kelp forests across the North Pacific Rim. *Global Ecology and Biogeography*, **30** (10), 2101–2118. https://doi.org/10.1111/geb.13370

142. Buttke, D., M. Wild, R. Monello, G. Schuurman, M. Hahn, and K. Jackson, 2021: Managing wildlife disease under climate change. *EcoHealth*, **18** (4), 406–410. https://doi.org/10.1007/s10393-021-01542-y

143. Hale, V.L., P.M. Dennis, D.S. McBride, J.M. Nolting, C. Madden, D. Huey, M. Ehrlich, J. Grieser, J. Winston, D. Lombardi, S. Gibson, L. Saif, M.L. Killian, K. Lantz, R.M. Tell, M. Torchetti, S. Robbe-Austerman, M.I. Nelson, S.A. Faith, and A.S. Bowman, 2022: SARS-CoV-2 infection in free-ranging white-tailed deer. *Nature*, **602** (7897), 481–486. https://doi.org/10.1038/s41586-021-04353-x

144. Harvell, C.D., D. Montecino-Latorre, J.M. Caldwell, J.M. Burt, K. Bosley, A. Keller, S.F. Heron, A.K. Salomon, L. Lee, O. Pontier, C. Pattengill-Semmens, and J.K. Gaydos, 2019: Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (*Pycnopodia helianthoides*). *Science Advances*, **5** (1), 7042. https://doi.org/10.1126/sciadv.aau7042

145. Harvell, D., 2019: *Ocean Outbreak: Confronting the Rising Tide of Marine Disease*. University of California Press, 232 pp. https://www.ucpress.edu/book/9780520382985/ocean-outbreak

146. Till, A., A.L. Rypel, A. Bray, and S.B. Fey, 2019: Fish die-offs are concurrent with thermal extremes in north temperate lakes. *Nature Climate Change*, **9**, 637–641. https://doi.org/10.1038/s41558-019-0520-y

147. Weiskopf, S.R., O.E. Ledee, and L.M. Thompson, 2019: Climate change effects on deer and moose in the Midwest. *The Journal of Wildlife Management*, **83** (4), 769–781. https://doi.org/10.1002/jwmg.21649

148. Cohen, J.M., M.D. Venesky, E.L. Sauer, D.J. Civitello, T.A. McMahon, E.A. Roznik, and J.R. Rohr, 2017: The thermal mismatch hypothesis explains host susceptibility to an emerging infectious disease. *Ecology Letters*, **20** (2), 184–193. https://doi.org/10.1111/ele.12720

149. Chaloner, T.M., S.J. Gurr, and D.P. Bebber, 2021: Plant pathogen infection risk tracks global crop yields under climate change. *Nature Climate Change*, **11** (8), 710–715. https://doi.org/10.1038/s41558-021-01104-8

150. Juroszek, P., P. Racca, S. Link, J. Farhumand, and B. Kleinhenz, 2020: Overview on the review articles published during the past 30 years relating to the potential climate change effects on plant pathogens and crop disease risks. *Plant Pathology*, **69** (2), 179–193. https://doi.org/10.1111/ppa.13119

151. Carlson, C.J., G.F. Albery, C. Merow, C.H. Trisos, C.M. Zipfel, E.A. Eskew, K.J. Olival, N. Ross, and S. Bansal, 2022: Climate change increases cross-species viral transmission risk. *Nature*, **607** (7919), 555–562. https://doi.org/10.1038/s41586-022-04788-w

152. Gilbert, L., 2021: The impacts of climate change on ticks and tick-borne disease risk. *Annual Review of Entomology*, **66** (1), 373–388. https://doi.org/10.1146/annurev-ento-052720-094533

153. Keesing, F. and R.S. Ostfeld, 2021: Impacts of biodiversity and biodiversity loss on zoonotic diseases. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (17), e2023540118. https://doi.org/10.1073/pnas.2023540118

154. Mora, C., T. McKenzie, I.M. Gaw, J.M. Dean, H. von Hammerstein, T.A. Knudson, R.O. Setter, C.Z. Smith, K.M. Webster, J.A. Patz, and E.C. Franklin, 2022: Over half of known human pathogenic diseases can be aggravated by climate change. *Nature Climate Change*, **12** (9), 869–875. https://doi.org/10.1038/s41558-022-01426-1

155. Islam, M.R., U. Bulut, T.P. Feria-Arroyo, M.G. Tyshenko, and T. Oraby, 2022: Modeling the impact of climate change on cervid chronic wasting disease in semi-arid south Texas. *Frontiers in Epidemiology*, **2**, 889280. https://doi.org/10.3389/fepid.2022.889280

156. Ogden, N.H., C. Ben Beard, H.S. Ginsberg, and J.I. Tsao, 2021: Possible effects of climate change on ixodid ticks and the pathogens they transmit: Predictions and observations. *Journal of Medical Entomology*, **58** (4), 1536–1545. https://doi.org/10.1093/jme/tjaa220

157. Sonenshine, D.E., 2018: Range expansion of tick disease vectors in North America: Implications for spread of tick-borne disease. *International Journal of Environmental Research and Public Health*, **15** (3), 478. https://doi.org/10.3390/ijerph15030478

158. Escobar, L.E., J. Escobar-Dodero, and N.B.D. Phelps, 2018: Infectious disease in fish: Global risk of viral hemorrhagic septicemia virus. *Reviews in Fish Biology and Fisheries*, **28** (3), 637–655. https://doi.org/10.1007/s11160-018-9524-3

159. Taylor, R.A., S.J. Ryan, C.A. Lippi, D.G. Hall, H.A. Narouei-Khandan, J.R. Rohr, and L.R. Johnson, 2019: Predicting the fundamental thermal niche of crop pests and diseases in a changing world: A case study on citrus greening. *Journal of Applied Ecology*, **56** (8), 2057–2068. https://doi.org/10.1111/1365-2664.13455

160. Singerman, A. and M.E. Rogers, 2020: The economic challenges of dealing with citrus greening: The case of Florida. *Journal of Integrated Pest Management*, **11** (1), 3. https://doi.org/10.1093/jipm/pmz037

161. Fortini, L.B., L.R. Kaiser, L.M. Keith, J. Price, R.F. Hughes, J.D. Jacobi, and J.B. Friday, 2019: The evolving threat of Rapid ʻŌhiʻa Death (ROD) to Hawai'i's native ecosystems and rare plant species. *Forest Ecology and Management*, **448**, 376–385. https://doi.org/10.1016/j.foreco.2019.06.025

162. Severud, W.J., M. Petz Giguere, T. Walters, T.J. Garwood, K. Teager, K.M. Marchetto, L. Gustavo R. Oliveira-Santos, S.A. Moore, and T.M. Wolf, 2023: Terrestrial gastropod species-specific responses to forest management: Implications for *Parelaphostrongylus tenuis* transmission to moose. *Forest Ecology and Management*, **529**, 120717. https://doi.org/10.1016/j.foreco.2022.120717

163. Walton, C.J., N.K. Hayes, and D.S. Gilliam, 2018: Impacts of a regional, multi-year, multi-species coral disease outbreak in southeast Florida. *Frontiers in Marine Science*, **5**, 323. https://doi.org/10.3389/fmars.2018.00323

164. Gervais, J.A., R. Kovach, A. Sepulveda, R. Al-Chokhachy, J. Joseph Giersch, and C.C. Muhlfeld, 2020: Climate-induced expansions of invasive species in the Pacific Northwest, North America: A synthesis of observations and projections. *Biological Invasions*, **22** (7), 2163–2183. https://doi.org/10.1007/s10530-020-02244-2

165. Seebens, H., S. Bacher, T.M. Blackburn, C. Capinha, W. Dawson, S. Dullinger, P. Genovesi, P.E. Hulme, M. van Kleunen, I. Kühn, J.M. Jeschke, B. Lenzner, A.M. Liebhold, Z. Pattison, J. Pergl, P. Pyšek, M. Winter, and F. Essl, 2021: Projecting the continental accumulation of alien species through to 2050. *Global Change Biology*, **27** (5), 970–982. https://doi.org/10.1111/gcb.15333

166. Hickman, J.E. and M.T. Lerdau, 2013: Biogeochemical impacts of the northward expansion of kudzu under climate change: The importance of ecological context. *Ecosphere*, **4** (10), art121. https://doi.org/10.1890/es13-00142.1

167. Stephens, K.L., M.E. Dantzler-Kyer, M.A. Patten, and L. Souza, 2019: Differential responses to global change of aquatic and terrestrial invasive species: Evidences from a meta-analysis. *Ecosphere*, **10** (4), e02680. https://doi.org/10.1002/ecs2.2680

168. Vilizzi, L., G.H. Copp, J.E. Hill, B. Adamovich, L. Aislabie, et al., 2021: A global-scale screening of non-native aquatic organisms to identify potentially invasive species under current and future climate conditions. *Science of The Total Environment*, **788**, 147868. https://doi.org/10.1016/j.scitotenv.2021.147868

169. Bellard, C., J.M. Jeschke, B. Leroy, and G.M. Mace, 2018: Insights from modeling studies on how climate change affects invasive alien species geography. *Ecology and Evolution*, **8** (11), 5688–5700. https://doi.org/10.1002/ece3.4098

170. Ellison, A.M., D.A. Orwig, M.C. Fitzpatrick, and E.L. Preisser, 2018: The past, present, and future of the hemlock woolly adelgid (*Adelges tsugae*) and its ecological interactions with eastern hemlock (*Tsuga canadensis*) forests. *Insects*, **9** (4), 172. https://doi.org/10.3390/insects9040172

171. Alsip, P.J., H. Zhang, M.D. Rowe, E. Rutherford, D.M. Mason, C. Riseng, and Z. Su, 2020: Modeling the interactive effects of nutrient loads, meteorology, and invasive mussels on suitable habitat for Bighead and Silver Carp in Lake Michigan. *Biological Invasions*, **22** (9), 2763–2785. https://doi.org/10.1007/s10530-020-02296-4

172. Patrick, D.A., N. Boudreau, Z. Bozic, G.S. Carpenter, D.M. Langdon, S.R. LeMay, S.M. Martin, R.M. Mourse, S.L. Prince, and K.M. Quinn, 2012: Effects of climate change on late-season growth and survival of native and non-native species of watermilfoil (*Myriophyllum* spp.): Implications for invasive potential and ecosystem change. *Aquatic Botany*, **103**, 83–88. https://doi.org/10.1016/j.aquabot.2012.06.008

173. Yamada, S.B., J.L. Fisher, and P.M. Kosro, 2021: Relationship between ocean ecosystem indicators and year class strength of the invasive European green crab (*Carcinus maenas*). *Progress in Oceanography*, **196**, 102618. https://doi.org/10.1016/j.pocean.2021.102618

174. Hoffmann, S., 2022: Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals. *Biodiversity and Conservation*, **31** (2), 325–352. https://doi.org/10.1007/s10531-021-02340-2

175. Kroeker, K.J., M.H. Carr, P.T. Raimondi, J.E. Caselle, L. Washburn, S.R. Palumbi, J.A. Barth, F. Chan, B.A. Menge, K. Milligan, M. Novak, and J.W. White, 2019: Planning for change: Assessing the potential role of marine protected areas and fisheries management approaches for resilience management in a changing ocean. *Oceanography*, **32** (3), 116–125. https://doi.org/10.5670/oceanog.2019.318

176. MassWildlife, 2015: Massachusetts State Wildlife Action Plan 2015. Massachusetts Division of Fisheries and Wildlife, Westborough, MA. https://www.mass.gov/service-details/state-wildlife-action-plan-swap

177. Staudinger, M.D., T.L. Morelli, and A.M. Bryan, 2015: Integrating Climate Change into Northeast and Midwest State Wildlife Action Plans. Northeast Climate Science Center, Amherst, MA, 201 pp. https://necasc.umass.edu/projects/integrating-climate-change-state-wildlife-action-plans

178. Zimmerer, R., T.L. Morelli, M. Ocana, and J. O'Leary, 2018: The Climate Project Screening Tool Report for the Massachusetts Division of Fisheries and Wildlife's Northeast District. MassWildlife. https://www.mass.gov/doc/northeast-district-climate-project-screening-tool-report/download

179. Carroll, C. and R.F. Noss, 2021: Rewilding in the face of climate change. *Conservation Biology*, **35** (1), 155–167. https://doi.org/10.1111/cobi.13531

180. Taylor, L., S.P. Saunders, J.X. Wu, B.L. Bateman, J. Grand, W.V. DeLuca, and C.B. Wilsey, 2022: Choice of prioritization method impacts recommendations for climate-informed bird conservation in the United States. *Ecography*, **2022** (12), e06401. https://doi.org/10.1111/ecog.06401

181. Keeley, A.T.H., D.D. Ackerly, D.R. Cameron, N.E. Heller, P.R. Huber, C.A. Schloss, J.H. Thorne, and A.M. Merenlender, 2018: New concepts, models, and assessments of climate-wise connectivity. *Environmental Research Letters*, **13** (7), 073002. https://doi.org/10.1088/1748-9326/aacb85

182. Besterman, A.F., R.W. Jakuba, W. Ferguson, D. Brennan, J.E. Costa, and L.A. Deegan, 2022: Buying time with runnels: A climate adaptation tool for salt marshes. *Estuaries and Coasts*, **45** (6), 1491–1501. https://doi.org/10.1007/s12237-021-01028-8

183. Wigand, C., T. Ardito, C. Chaffee, W. Ferguson, S. Paton, K. Raposa, C. Vandemoer, and E. Watson, 2017: A climate change adaptation strategy for management of coastal marsh systems. *Estuaries and Coasts*, **40** (3), 682–693. https://doi.org/10.1007/s12237-015-0003-y

184. Butt, N., A.L.M. Chauvenet, V.M. Adams, M. Beger, R.V. Gallagher, D.F. Shanahan, M. Ward, J.E.M. Watson, and H.P. Possingham, 2021: Importance of species translocations under rapid climate change. *Conservation Biology*, **35** (3), 775–783. https://doi.org/10.1111/cobi.13643

185. Palik, B.J., P.W. Clark, A.W. D'Amato, C. Swanston, and L. Nagel, 2022: Operationalizing forest-assisted migration in the context of climate change adaptation: Examples from the eastern USA. *Ecosphere*, **13** (10), e4260. https://doi.org/10.1002/ecs2.4260

186. Orning, E.K., M.C. Romanski, S. Moore, Y. Chenaux-Ibrahim, J. Hart, and J.L. Belant, 2020: Emigration and first-year movements of initial Wolf translocations to Isle Royale. *Northeastern Naturalist*, **27** (4), 701–708. https://doi.org/10.1656/045.027.0410

187. Gonzalez, P., F. Wang, M. Notaro, D.J. Vimont, and J.W. Williams, 2018: Disproportionate magnitude of climate change in United States national parks. *Environmental Research Letters*, **13** (10), 104001. https://doi.org/10.1088/1748-9326/aade09

188. Hoffmann, S., S.D.H. Irl, and C. Beierkuhnlein, 2019: Predicted climate shifts within terrestrial protected areas worldwide. *Nature Communications*, **10** (1), 4787. https://doi.org/10.1038/s41467-019-12603-w

189. Wilson, K.L., D.P. Tittensor, B. Worm, and H.K. Lotze, 2020: Incorporating climate change adaptation into marine protected area planning. *Global Change Biology*, **26** (6), 3251–3267. https://doi.org/10.1111/gcb.15094

190. Holsinger, L., S.A. Parks, M.-A. Parisien, C. Miller, E. Batllori, and M.A. Moritz, 2019: Climate change likely to reshape vegetation in North America's largest protected areas. *Conservation Science and Practice*, **1** (7), e50. https://doi.org/10.1111/csp2.50

191. Suraci, J.P., L.S. Farwell, C.E. Littlefield, P.T. Freeman, L.J. Zachmann, V.A. Landau, J.J. Anderson, and B.G. Dickson, 2023: Achieving conservation targets by jointly addressing climate change and biodiversity loss. *Ecosphere*, **14** (4), e4490. https://doi.org/10.1002/ecs2.4490

192. Lawler, J.J., D.S. Rinnan, J.L. Michalak, J.C. Withey, C.R. Randels, and H.P. Possingham, 2020: Planning for climate change through additions to a national protected area network: Implications for cost and configuration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190117. https://doi.org/10.1098/rstb.2019.0117

193. Wu, J.X., B.L. Bateman, P.J. Heglund, L. Taylor, A.J. Allstadt, D. Granfors, H. Westerkam, N.L. Michel, and C.B. Wilsey, 2022: U.S. National Wildlife Refuge System likely to see regional and seasonal species turnover in bird assemblages under a 2°C warming scenario. *Ornithological Applications*, **124** (3), 016. https://doi.org/10.1093/ornithapp/duac016

194. Wu, J.X., C.B. Wilsey, L. Taylor, and G.W. Schuurman, 2018: Projected avifaunal responses to climate change across the U.S. National Park System. *PLoS ONE*, **13** (3), e0190557. https://doi.org/10.1371/journal.pone.0190557

195. Froese, R. and J. Schilling, 2019: The nexus of climate change, land use, and conflicts. *Current Climate Change Reports*, **5** (1), 24–35. https://doi.org/10.1007/s40641-019-00122-1

196. Koubi, V., 2019: Climate change and conflict. *Annual Review of Political Science*, **22** (1), 343–360. https://doi.org/10.1146/annurev-polisci-050317-070830

197. Dubik, B.A., E.C. Clark, T. Young, S.B.J. Zigler, M.M. Provost, M.L. Pinsky, and K. St. Martin, 2019: Governing fisheries in the face of change: Social responses to long-term geographic shifts in a U.S. fishery. *Marine Policy*, **99**, 243–251. https://doi.org/10.1016/j.marpol.2018.10.032

198. Palacios-Abrantes, J., T.L. Frölicher, G. Reygondeau, U.R. Sumaila, A. Tagliabue, Colette C.C. Wabnitz, and William W.L. Cheung, 2022: Timing and magnitude of climate-driven range shifts in transboundary fish stocks challenge their management. *Global Change Biology*, **28** (7), 2312–2326. https://doi.org/10.1111/gcb.16058

199. Berger-Tal, O., D.T. Blumstein, and R.R. Swaisgood, 2020: Conservation translocations: A review of common difficulties and promising directions. *Animal Conservation*, **23** (2), 121–131. https://doi.org/10.1111/acv.12534

200. Mach, K.J., C.M. Kraan, W.N. Adger, H. Buhaug, M. Burke, J.D. Fearon, C.B. Field, C.S. Hendrix, J.-F. Maystadt, J. O'Loughlin, P. Roessler, J. Scheffran, K.A. Schultz, and N. von Uexkull, 2019: Climate as a risk factor for armed conflict. *Nature*, **571** (7764), 193–197. https://doi.org/10.1038/s41586-019-1300-6

201. Pinsky, M.L., L.A. Rogers, J.W. Morley, and T.L. Frölicher, 2020: Ocean planning for species on the move provides substantial benefits and requires few trade-offs. *Science Advances*, **6** (50), 8428. https://doi.org/10.1126/sciadv.abb8428

202. Himes, A. and B. Muraca, 2018: Relational values: The key to pluralistic valuation of ecosystem services. *Current Opinion in Environmental Sustainability*, **35**, 1–7. https://doi.org/10.1016/j.cosust.2018.09.005

203. Michaelis, A.K., W.C. Walton, D.W. Webster, and L.J. Shaffer, 2021: Cultural ecosystem services enabled through work with shellfish. *Marine Policy*, **132**, 104689. https://doi.org/10.1016/j.marpol.2021.104689

204. Dam Lam, R., A. Gasparatos, S. Chakraborty, H. Rivera, and T. Stanley, 2019: Multiple values and knowledge integration in indigenous coastal and marine social-ecological systems research: A systematic review. *Ecosystem Services*, **37**, 100910. https://doi.org/10.1016/j.ecoser.2019.100910

205. Mockta, T.K., P.Z. Fulé, A. Sánchez Meador, T. Padilla, and Y.-S. Kim, 2018: Sustainability of culturally important teepee poles on Mescalero Apache Tribal Lands: Characteristics and climate change effects. *Forest Ecology and Management*, **430**, 250–258. https://doi.org/10.1016/j.foreco.2018.08.017

206. O'Connor, S. and J.O. Kenter, 2019: Making intrinsic values work: Integrating intrinsic values of the more-than-human world through the Life Framework of Values. *Sustainability Science*, **14** (5), 1247–1265. https://doi.org/10.1007/s11625-019-00715-7

207. Runting, R.K., B.A. Bryan, L.E. Dee, F.J.F. Maseyk, L. Mandle, P. Hamel, K.A. Wilson, K. Yetka, H.P. Possingham, and J.R. Rhodes, 2017: Incorporating climate change into ecosystem service assessments and decisions: A review. *Global Change Biology*, **23** (1), 28–41. https://doi.org/10.1111/gcb.13457

208. Warziniack, T., M. Lawson, and S. Karen Dante-Wood, 2018: Ch. 10. Effects of climate change on ecosystem services in the Northern Rockies. In: *Climate Change and Rocky Mountain Ecosystems*. Halofsky, J.E. and D.L. Peterson, Eds. Springer, Cham, Switzerland, 189–208. https://doi.org/10.1007/978-3-319-56928-4_10

209. Brice, E.M., B.A. Miller, H. Zhang, K. Goldstein, S.N. Zimmer, G.J. Grosklos, P. Belmont, C.G. Flint, J.E. Givens, P.B. Adler, M.W. Brunson, and J.W. Smith, 2020: Impacts of climate change on multiple use management of Bureau of Land Management land in the Intermountain West, USA. *Ecosphere*, **11** (11), e03286. https://doi.org/10.1002/ecs2.3286

210. Wilkins, E.J., Y. Chikamoto, A.B. Miller, and J.W. Smith, 2021: Climate change and the demand for recreational ecosystem services on public lands in the continental United States. *Global Environmental Change*, **70**, 102365. https://doi.org/10.1016/j.gloenvcha.2021.102365

211. Martin, D.M., J.A. Specht, M.R. Canick, K.L. Leo, and K. Freeman, 2022: Using decision analysis to integrate habitat and community values for coastal resilience planning. *Estuaries and Coasts*, **45** (2), 331–344. https://doi.org/10.1007/s12237-021-00970-x

212. Meerow, S., 2019: A green infrastructure spatial planning model for evaluating ecosystem service tradeoffs and synergies across three coastal megacities. *Environmental Research Letters*, **14** (12), 125011. https://doi.org/10.1088/1748-9326/ab502c

213. Alves Carvalho Nascimento, L. and V. Shandas, 2021: Integrating diverse perspectives for managing neighborhood trees and urban ecosystem services in Portland, OR (US). *Land*, **10** (1), 48. https://doi.org/10.3390/land10010048

214. Herreros-Cantis, P. and T. McPhearson, 2021: Mapping supply of and demand for ecosystem services to assess environmental justice in New York City. *Ecological Applications*, **31** (6), e02390. https://doi.org/10.1002/eap.2390

215. Richards, D.R., R.N. Belcher, L.R. Carrasco, P.J. Edwards, S. Fatichi, P. Hamel, M. Masoudi, M.J. McDonnell, N. Peleg, and M.C. Stanley, 2022: Global variation in contributions to human well-being from urban vegetation ecosystem services. *One Earth*, **5** (5), 522–533. https://doi.org/10.1016/j.oneear.2022.04.006

216. Anguelovski, I., J.J. Connolly, M. Garcia-Lamarca, H. Cole, and H. Pearsall, 2019: New scholarly pathways on green gentrification: What does the urban 'green turn' mean and where is it going? *Progress in Human Geography*, **43** (6), 1064–1086. https://doi.org/10.1177/0309132518803799

217. Rigolon, A. and J. Németh, 2018: "We're not in the business of housing:" Environmental gentrification and the nonprofitization of green infrastructure projects. *Cities*, **81**, 71–80. https://doi.org/10.1016/j.cities.2018.03.016

218. Hendricks, M.D. and S. Van Zandt, 2021: Unequal protection revisited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. *Environmental Justice*, **14** (2), 87–97. https://doi.org/10.1089/env.2020.0054

219. Schell, C.J., K. Dyson, T.L. Fuentes, S.D. Roches, N.C. Harris, D.S. Miller, C.A. Woelfle-Erskine, and M.R. Lambert, 2020: The ecological and evolutionary consequences of systemic racism in urban environments. *Science*, **369** (6510), 4497. https://doi.org/10.1126/science.aay4497

220. EPA, 2022: EPA's Report on the Environment (ROE). U.S. Environmental Protection Agency. https://www.epa.gov/report-environment

221. Sanders, B.F., J.E. Schubert, D.T. Kahl, K.J. Mach, D. Brady, A. AghaKouchak, F. Forman, R.A. Matthew, N. Ulibarri, and S.J. Davis, 2023: Large and inequitable flood risks in Los Angeles, California. *Nature Sustainability*, **6** (1), 47–57. https://doi.org/10.1038/s41893-022-00977-7

222. Ma, S., C.A. Craig, and S. Feng, 2021: Camping climate resources: The camping climate index in the United States. *Current Issues in Tourism*, **24** (18), 2523–2531. https://doi.org/10.1080/13683500.2020.1846503

223. Nesbitt, L., M.J. Meitner, C. Girling, S.R.J. Sheppard, and Y. Lu, 2019: Who has access to urban vegetation? A spatial analysis of distributional green equity in 10 US cities. *Landscape and Urban Planning*, **181**, 51–79. https://doi.org/10.1016/j.landurbplan.2018.08.007

224. Spotswood, E.N., M. Benjamin, L. Stoneburner, M.M. Wheeler, E.E. Beller, D. Balk, T. McPhearson, M. Kuo, and R.I. McDonald, 2021: Nature inequity and higher COVID-19 case rates in less-green neighbourhoods in the United States. *Nature Sustainability*, **4** (12), 1092–1098. https://doi.org/10.1038/s41893-021-00781-9

225. Stewart, I.T., J. Rogers, and A. Graham, 2020: Water security under severe drought and climate change: Disparate impacts of the recent severe drought on environmental flows and water supplies in central California. *Journal of Hydrology* X, **7**, 100054. https://doi.org/10.1016/j.hydroa.2020.100054

226. Drugova, T., K.R. Curtis, and M.-K. Kim, 2022: The impacts of drought on Southwest tribal economies. JAWRA *Journal of the American Water Resources Association*, **58** (5), 639–653. https://doi.org/10.1111/1752-1688.13018

227. McBride, J.R. and I. Laćan, 2018: The impact of climate-change induced temperature increases on the suitability of street tree species in California (USA) cities. *Urban Forestry & Urban Greening*, **34**, 348–356. https://doi.org/10.1016/j.ufug.2018.07.020

228. Daouda, M., L. Henneman, J. Goldsmith, M.-A. Kioumourtzoglou, and A. Casey Joan, 2022: Racial/ethnic disparities in nationwide $PM_{2.5}$ concentrations: Perils of assuming a linear relationship. *Environmental Health Perspectives*, **130** (7), 077701. https://doi.org/10.1289/ehp11048

229. Tessum, C.W., J.S. Apte, A.L. Goodkind, N.Z. Muller, K.A. Mullins, D.A. Paolella, S. Polasky, N.P. Springer, S.K. Thakrar, J.D. Marshall, and J.D. Hill, 2019: Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6001–6006. https://doi.org/10.1073/pnas.1818859116

230. Tessum, C.W., D.A. Paolella, S.E. Chambliss, J.S. Apte, J.D. Hill, and J.D. Marshall, 2021: $PM_{2.5}$ polluters disproportionately and systemically affect people of color in the United States. *Science Advances*, **7** (18), 4491. https://doi.org/10.1126/sciadv.abf4491

231. Lane, H.M., R. Morello-Frosch, J.D. Marshall, and J.S. Apte, 2022: Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environmental Science & Technology Letters*, **9** (4), 345–350. https://doi.org/10.1021/acs.estlett.1c01012

232. Staudinger, M.D., A.J. Lynch, S.K. Gaichas, M.G. Fox, D. Gibson-Reinemer, J.A. Langan, A.K. Teffer, S.J. Thackeray, and I.J. Winfield, 2021: How does climate change affect emergent properties of aquatic ecosystems? *Fisheries*, **46** (9), 423–441. https://doi.org/10.1002/fsh.10606

233. Crozier, L.G., B.J. Burke, B.E. Chasco, D.L. Widener, and R.W. Zabel, 2021: Climate change threatens Chinook salmon throughout their life cycle. *Communications Biology*, **4** (1), 222. https://doi.org/10.1038/s42003-021-01734-w

234. Cohen-Shacham, E., A. Andrade, J. Dalton, N. Dudley, M. Jones, C. Kumar, S. Maginnis, S. Maynard, C.R. Nelson, F.G. Renaud, R. Welling, and G. Walters, 2019: Core principles for successfully implementing and upscaling Nature-based Solutions. *Environmental Science & Policy*, **98**, 20–29. https://doi.org/10.1016/j.envsci.2019.04.014

235. Griscom, B.W., J. Adams, P.W. Ellis, R.A. Houghton, G. Lomax, D.A. Miteva, W.H. Schlesinger, D. Shoch, J.V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R.T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M.R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S.M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F.E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, and J. Fargione, 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

236. Roelvink, F.E., C.D. Storlazzi, A.R. van Dongeren, and S.G. Pearson, 2021: Coral reef restorations can be optimized to reduce coastal flooding hazards. *Frontiers in Marine Science*, **8**, 653945. https://doi.org/10.3389/fmars.2021.653945

237. Morecroft, M.D., S. Duffield, M. Harley, J.W. Pearce-Higgins, N. Stevens, O. Watts, and J. Whitaker, 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science*, **366** (6471), 9256. https://doi.org/10.1126/science.aaw9256

238. Guerry, A.D., J. Silver, J. Beagle, K. Wyatt, K. Arkema, J. Lowe, P. Hamel, R. Griffin, S. Wolny, E. Plane, M. Griswold, H. Papendick, and J. Sharma, 2022: Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise. *npj Urban Sustainability*, **2** (1), 13. https://doi.org/10.1038/s42949-022-00056-y

239. Schelske, O., J.R. Bohn, and C. Fitzgerald, 2021: Ch. 19. Insuring natural ecosystems as an innovative conservation funding mechanism: A case study on coral reefs. In: *Handbook of Disaster Risk Reduction for Resilience: New Frameworks for Building Resilience to Disasters*. Eslamian, S. and F. Eslamian, Eds. Springer, Cham, Switzerland, 435–452. https://doi.org/10.1007/978-3-030-61278-8_19

240. Akamani, K. and T.E. Hall, 2019: Scale and co-management outcomes: Assessing the impact of collaborative forest management on community and household resilience in Ghana. *Heliyon*, **5** (1), e01125. https://doi.org/10.1016/j.heliyon.2019.e01125

241. Jones, H.P., B. Nickel, T. Srebotnjak, W. Turner, M. Gonzalez-Roglich, E. Zavaleta, and D.G. Hole, 2020: Global hotspots for coastal ecosystem-based adaptation. *PLoS ONE*, **15** (5), e0233005. https://doi.org/10.1371/journal.pone.0233005

242. Peck, A.J., S.L. Adams, A. Armstrong, A.K. Bartlett, M.L. Bortman, A.B. Branco, M.L. Brown, J.L. Donohue, M.o. Kodis, M.J. McCann, and E. Smith, 2022: A new framework for flood adaptation: Introducing the Flood Adaptation Hierarchy. *Ecology and Society*, **27** (4). https://doi.org/10.5751/es-13544-270405

243. Donatti, C.I., C.A. Harvey, D. Hole, S.N. Panfil, and H. Schurman, 2020: Indicators to measure the climate change adaptation outcomes of ecosystem-based adaptation. *Climatic Change*, **158** (3), 413–433. https://doi.org/10.1007/s10584-019-02565-9

244. Beck, M.W., N. Heck, S. Narayan, P. Menéndez, B.G. Reguero, S. Bitterwolf, S. Torres-Ortega, G.-M. Lange, K. Pfliegner, V. Pietsch McNulty, and I.J. Losada, 2022: Return on investment for mangrove and reef flood protection. *Ecosystem Services*, **56**, 101440. https://doi.org/10.1016/j.ecoser.2022.101440

245. Reguero, B.G., C.D. Storlazzi, A.E. Gibbs, J.B. Shope, A.D. Cole, K.A. Cumming, and M.W. Beck, 2021: The value of US coral reefs for flood risk reduction. *Nature Sustainability*, **4** (8), 688–698. https://doi.org/10.1038/s41893-021-00706-6

246. Ferreira, V., A.P. Barreira, L. Loures, D. Antunes, and T. Panagopoulos, 2020: Stakeholders' engagement on nature-based solutions: A systematic literature review. *Sustainability*, **12** (2), 640. https://doi.org/10.3390/su12020640

247. Hoover, F.-A., S. Meerow, Z.J. Grabowski, and T. McPhearson, 2021: Environmental justice implications of siting criteria in urban green infrastructure planning. *Journal of Environmental Policy & Planning*, **23** (5), 665–682. https://doi.org/10.1080/1523908x.2021.1945916

248. Jordan, P., F.-A. Hoover, and M.E. Hopton, 2022: Leveraging ancillary benefits from urban greenspace—A case study of St. Louis, Missouri. *Urban Water Journal*, **19** (3), 314–323. https://doi.org/10.1080/1573062x.2021.2001544

249. Jurjonas, M. and E. Seekamp, 2020: 'A commons before the sea:' Climate justice considerations for coastal zone management. *Climate and Development*, **12** (3), 199–203. https://doi.org/10.1080/17565529.2019.1611533

250. Shi, L., 2020: Beyond flood risk reduction: How can green infrastructure advance both social justice and regional impact? *Socio-Ecological Practice Research*, **2** (4), 311–320. https://doi.org/10.1007/s42532-020-00065-0

251. Vasseur, L., 2021: How ecosystem-based adaptation to climate change can help coastal communities through a participatory approach. *Sustainability*, **13** (4), 2344. https://doi.org/10.3390/su13042344

252. Croeser, T., G. Garrard, R. Sharma, A. Ossola, and S. Bekessy, 2021: Choosing the right nature-based solutions to meet diverse urban challenges. *Urban Forestry & Urban Greening*, **65**, 127337. https://doi.org/10.1016/j.ufug.2021.127337

253. Howie, A.H. and M.J. Bishop, 2021: Contemporary oyster reef restoration: Responding to a changing world. *Frontiers in Ecology and Evolution*, **9**, 689915. https://doi.org/10.3389/fevo.2021.689915

254. Kaye, J.P. and M. Quemada, 2017: Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for Sustainable Development*, **37** (1), 1–17. https://doi.org/10.1007/s13593-016-0410-x

255. Law, B.E., L.T. Berner, P.C. Buotte, D.J. Mildrexler, and W.J. Ripple, 2021: Strategic Forest Reserves can protect biodiversity in the western United States and mitigate climate change. *Communications Earth & Environment*, **2** (1), 254. https://doi.org/10.1038/s43247-021-00326-0

256. Carroll, C. and J.C. Ray, 2021: Maximizing the effectiveness of national commitments to protected area expansion for conserving biodiversity and ecosystem carbon under climate change. *Global Change Biology*, **27** (15), 3395–3414. https://doi.org/10.1111/gcb.15645

257. Malhi, Y., T. Lander, E. le Roux, N. Stevens, M. Macias-Fauria, L. Wedding, C. Girardin, J.Å. Kristensen, C.J. Sandom, T.D. Evans, J.-C. Svenning, and S. Canney, 2022: The role of large wild animals in climate change mitigation and adaptation. *Current Biology*, **32** (4), R181–R196. https://doi.org/10.1016/j.cub.2022.01.041

258. Seddon, N., A. Chausson, P. Berry, C.A.J. Girardin, A. Smith, and B. Turner, 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

259. Fargione, J.E., S. Bassett, T. Boucher, S.D. Bridgham, R.T. Conant, S.C. Cook-patton, P.W. Ellis, A. Falcucci, J.W. Fourqurean, T. Gopalakrishna, H. Gu, B. Henderson, M.D. Hurteau, K.D. Kroeger, T. Kroeger, T.J. Lark, S.M. Leavitt, G. Lomax, R.I. McDonald, J.P. Megonigal, D.A. Miteva, C.J. Richardson, J. Sanderman, D. Shoch, S.A. Spawn, J.W. Veldman, C.A. WIlliams, P.B. Woodbury, C. Zganjar, M. Baranski, R.A. Houghton, E. Landis, E. McGlynn, W.H. Schlesinger, J.V. Siikamakiariana, E. Sutton-Grierand, and B.W. Griscom, 2018: Natural climate solutions for the United States. *Science Advances*, **4** (11), 1869. https://doi.org/10.1126/sciadv.aat1869

260. Shaver, E.C., E. McLeod, M.Y. Hein, S.R. Palumbi, K. Quigley, T. Vardi, P.J. Mumby, D. Smith, P. Montoya-Maya, E.M. Muller, A.T. Banaszak, I.M. McLeod, and D. Wachenfeld, 2022: A roadmap to integrating resilience into the practice of coral reef restoration. *Global Change Biology*, **28** (16), 4751–4764. https://doi.org/10.1111/gcb.16212

261. Taillardat, P., B.S. Thompson, M. Garneau, K. Trottier, and D.A. Friess, 2020: Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. *Interface Focus*, **10** (5), 20190129. https://doi.org/10.1098/rsfs.2019.0129

262. Kashuba, R., C. Menzie, and L. Martin, 2021: Risk of cardiovascular disease is driven by different combinations of environmental, medical and behavioral factors: Building a conceptual model for cumulative risk assessment. *Human and Ecological Risk Assessment: An International Journal*, **27** (7), 1902–1925. https://doi.org/10.1080/10807039.2021.1925083

263. McDonald, T., G.D. Gann, J. Jonson, and K.W. Dixon, 2016: International Standards for the Practice of Ecological Restoration—Including Principles and Key Concepts. Society for Ecological Restoration, Washington, DC. https://seraustralasia.com/wheel/image/SER_International_Standards.pdf

264. Carruthers, T.J.B., E.P. Kiskaddon, M.M. Baustian, K.M. Darnell, L.C. Moss, C.L. Perry, and C. Stagg, 2022: Tradeoffs in habitat value to maximize natural resource benefits from coastal restoration in a rapidly eroding wetland: Is monitoring land area sufficient? *Restoration Ecology*, **30** (4), e13564. https://doi.org/10.1111/rec.13564

265. Lavorel, S., B. Locatelli, M.J. Colloff, and E. Bruley, 2020: Co-producing ecosystem services for adapting to climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190119. https://doi.org/10.1098/rstb.2019.0119

266. Li, R., H. Zheng, P. O'Connor, H. Xu, Y. Li, F. Lu, B.E. Robinson, Z. Ouyang, Y. Hai, and G.C. Daily, 2021: Time and space catch up with restoration programs that ignore ecosystem service trade-offs. *Science Advances*, **7** (14), 8650. https://doi.org/10.1126/sciadv.abf8650

267. Rossi, R., C. Bisland, L. Sharpe, E. Trentacoste, B. Williams, and S. Yee, 2022: Identifying and aligning ecosystem services and beneficiaries associated with best management practices in Chesapeake Bay watershed. *Environmental Management*, **69** (2), 384–409. https://doi.org/10.1007/s00267-021-01561-z

268. Smardon, R., S. Moran, and A.K. Baptiste, 2018: *Revitalizing Urban Waterway Communities: Streams of Environmental Justice*. Routledge, London, UK and New York, USA, 228 pp. https://www.routledge.com/revitalizing-urban-waterway-communities-streams-of-environmental-justice/smardon-moran-baptiste/p/book/9780367605896

269. Dockry, M.J. and S.J. Hoagland, 2017: A special issue of the *Journal of Forestry*—Tribal forest management: Innovations for sustainable forest management. *Journal of Forestry*, **115** (5), 339–340. https://doi.org/10.5849/jof-2017-040

270. Jacobson, M.A., R. Hajjar, E.J. Davis, and S. Hoagland, 2021: Learning from tribal leadership and the anchor forest concept for implementing cross-boundary forest management. *Journal of Forestry*, **119** (6), 605–617. https://doi.org/10.1093/jofore/fvab031

271. Long, J.W., R.W. Goode, and F.K. Lake, 2020: Recentering ecological restoration with tribal perspectives. *Fremontia*, **48** (1), 14–19. https://www.fs.usda.gov/research/treesearch/61600

272. Reyes-García, V., Á. Fernández-Llamazares, P. McElwee, Z. Molnár, K. Öllerer, S.J. Wilson, and E.S. Brondizio, 2019: The contributions of Indigenous Peoples and local communities to ecological restoration. *Restoration Ecology*, **27** (1), 3–8. https://doi.org/10.1111/rec.12894

273. Biggs, R., G. D. Peterson, and J. C. Rocha, 2018: The regime shifts database: A framework for analyzing regime shifts in social-ecological systems. *Ecology and Society*, **23** (3), 9. https://doi.org/10.5751/es-10264-230309

274. Breshears, D.D., C.J.W. Carroll, M.D. Redmond, A.P. Wion, C.D. Allen, N.S. Cobb, N. Meneses, J.P. Field, L.A. Wilson, D.J. Law, L.M. McCabe, and O. Newell-Bauer, 2018: A dirty dozen ways to die: Metrics and modifiers of mortality driven by drought and warming for a tree species. *Frontiers in Forests and Global Change*, **1**, 4. https://doi.org/10.3389/ffgc.2018.00004

275. Canadell, J.G. and R.B. Jackson, Eds., 2021: *Ecosystem Collapse and Climate Change*. Springer, Cham, Switzerland, 366 pp. https://doi.org/10.1007/978-3-030-71330-0

276. Davis, K.T., S.Z. Dobrowski, P.E. Higuera, Z.A. Holden, T.T. Veblen, M.T. Rother, S.A. Parks, A. Sala, and M.P. Maneta, 2019: Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6193–6198. https://doi.org/10.1073/pnas.1815107116

277. Stevens-Rumann, C.S., K.B. Kemp, P.E. Higuera, B.J. Harvey, M.T. Rother, D.C. Donato, P. Morgan, and T.T. Veblen, 2018: Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters*, **21** (2), 243–252. https://doi.org/10.1111/ele.12889

278. Guiterman, C.H., E.Q. Margolis, C.D. Allen, D.A. Falk, and T.W. Swetnam, 2018: Long-term persistence and fire resilience of oak shrubfields in dry conifer forests of northern New Mexico. *Ecosystems*, **21** (5), 943–959. https://www.jstor.org/stable/48719582

279. O'Connor, C.D., D.A. Falk, and G.M. Garfin, 2020: Projected climate-fire interactions drive forest to shrubland transition on an Arizona Sky Island. *Frontiers in Environmental Science*, **8**, 137. https://doi.org/10.3389/fenvs.2020.00137

280. van Mantgem, P.J., D.A. Falk, E.C. Williams, A.J. Das, and N.L. Stephenson, 2020: The influence of pre-fire growth patterns on post-fire tree mortality for common conifers in western US parks. *International Journal of Wildland Fire*, **29** (6), 513–518. https://doi.org/10.1071/wf19020

281. Allen, J.M. and B.A. Bradley, 2016: Out of the weeds? Reduced plant invasion risk with climate change in the continental United States. *Biological Conservation*, **203**, 306–312. https://doi.org/10.1016/j.biocon.2016.09.015

282. Crall, A.W., G.J. Newman, C.S. Jarnevich, T.J. Stohlgren, D.M. Waller, and J. Graham, 2010: Improving and integrating data on invasive species collected by citizen scientists. *Biological Invasions*, **12** (10), 3419–3428. https://doi.org/10.1007/s10530-010-9740-9

283. Lázaro-Lobo, A., R.D. Lucardi, C. Ramirez-Reyes, and G.N. Ervin, 2021: Region-wide assessment of fine-scale associations between invasive plants and forest regeneration. *Forest Ecology and Management*, **483**, 118930. https://doi.org/10.1016/j.foreco.2021.118930

284. Prevéy, J., M. Vellend, N. Rüger, R.D. Hollister, A.D. Bjorkman, I.H. Myers-Smith, S.C. Elmendorf, K. Clark, E.J. Cooper, B. Elberling, A.M. Fosaa, G.H.R. Henry, T.T. Høye, I.S. Jónsdóttir, K. Klanderud, E. Lévesque, M. Mauritz, U. Molau, S.M. Natali, S.F. Oberbauer, Z.A. Panchen, E. Post, S.B. Rumpf, N.M. Schmidt, E.A.G. Schuur, P.R. Semenchuk, T. Troxler, J.M. Welker, and C. Rixen, 2017: Greater temperature sensitivity of plant phenology at colder sites: Implications for convergence across northern latitudes. *Global Change Biology*, **23** (7), 2660–2671. https://doi.org/10.1111/gcb.13619

285. Boyd, P.W., S. Collins, S. Dupont, K. Fabricius, J.-P. Gattuso, J. Havenhand, D.A. Hutchins, U. Riebesell, M.S. Rintoul, M. Vichi, H. Biswas, A. Ciotti, K. Gao, M. Gehlen, C.L. Hurd, H. Kurihara, C.M. McGraw, J.M. Navarro, G.E. Nilsson, U. Passow, and H.-O. Pörtner, 2018: Experimental strategies to assess the biological ramifications of multiple drivers of global ocean change—A review. *Global Change Biology*, **24** (6), 2239–2261. https://doi.org/10.1111/gcb.14102

286. Turley, C. and J.-P. Gattuso, 2012: Future biological and ecosystem impacts of ocean acidification and their socioeconomic-policy implications. *Current Opinion in Environmental Sustainability*, **4** (3), 278–286. https://doi.org/10.1016/j.cosust.2012.05.007

287. Agne, M.C., P.A. Beedlow, D.C. Shaw, D.R. Woodruff, E.H. Lee, S.P. Cline, and R.L. Comeleo, 2018: Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. *Forest Ecology and Management*, **409**, 317–332. https://doi.org/10.1016/j.foreco.2017.11.004

288. Seidl, R., D. Thom, M. Kautz, D. Martin-Benito, M. Peltoniemi, G. Vacchiano, J. Wild, D. Ascoli, M. Petr, J. Honkaniemi, M.J. Lexer, V. Trotsiuk, P. Mairota, M. Svoboda, M. Fabrika, T.A. Nagel, and C.P.O. Reyer, 2017: Forest disturbances under climate change. *Nature Climate Change*, **7** (6), 395–402. https://doi.org/10.1038/nclimate3303

289. Finch, D.M., J.L. Butler, J.B. Runyon, C.J. Fettig, F.F. Kilkenny, S. Jose, S.J. Frankel, S.A. Cushman, R.C. Cobb, J.S. Dukes, J.A. Hicke, and S.K. Amelon, 2021: Ch. 4. Effects of climate change on invasive species. In: *Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector*. Poland, T.M., T. Patel-Weynand, D.M. Finch, C.F. Miniat, D.C. Hayes, and V.M. Lopez, Eds. Springer, Cham, Switzerland, 57–83. https://doi.org/10.1007/978-3-030-45367-1_4

290. Gandhi, K. and R. Hofstetter, Eds., 2021: *Bark Beetle Management, Ecology, and Climate Change*. Academic Press. https://doi.org/10.1016/c2019-0-04282-3

291. Jactel, H., J. Koricheva, and B. Castagneyrol, 2019: Responses of forest insect pests to climate change: Not so simple. *Current Opinion in Insect Science*, **35**, 103–108. https://doi.org/10.1016/j.cois.2019.07.010

292. Lopez, B.E., J.M. Allen, J.S. Dukes, J. Lenoir, M. Vilà, D.M. Blumenthal, E.M. Beaury, E.J. Fusco, B.B. Laginhas, T.L. Morelli, M.W. O'Neill, C.J.B. Sorte, A. Maceda-Veiga, R. Whitlock, and B.A. Bradley, 2022: Global environmental changes more frequently offset than intensify detrimental effects of biological invasions. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (22), e2117389119. https://doi.org/10.1073/pnas.2117389119

293. Lucash, M.S., R.M. Scheller, B.R. Sturtevant, E.J. Gustafson, A.M. Kretchun, and J.R. Foster, 2018: More than the sum of its parts: How disturbance interactions shape forest dynamics under climate change. *Ecosphere*, **9** (6), e02293. https://doi.org/10.1002/ecs2.2293

294. Hastings, A., K.C. Abbott, K. Cuddington, T. Francis, G. Gellner, Y.-C. Lai, A. Morozov, S. Petrovskii, K. Scranton, and M.L. Zeeman, 2018: Transient phenomena in ecology. *Science*, **361** (6406), 6412. https://doi.org/10.1126/science.aat6412

295. Hughes, T.P., C. Linares, V. Dakos, I.A. van de Leemput, and E.H. van Nes, 2013: Living dangerously on borrowed time during slow, unrecognized regime shifts. *Trends in Ecology & Evolution*, **28** (3), 149–155. https://doi.org/10.1016/j.tree.2012.08.022

296. Tang, B., J.S. Clark, and A.E. Gelfand, 2021: Modeling spatially biased citizen science effort through the eBird database. *Environmental and Ecological Statistics*, **28** (3), 609–630. https://doi.org/10.1007/s10651-021-00508-1

297. Olsson, P., V. Galaz, and W.J. Boonstra, 2014: Sustainability transformations: A resilience perspective. *Ecology and Society*, **19** (4). https://doi.org/10.5751/es-06799-190401

298. Walker, B., S.R. Carpenter, C. Folke, L. Gunderson, G.D. Peterson, M. Scheffer, M. Schoon, and F.R. Westley, 2020: Navigating the chaos of an unfolding global cycle. *Ecology and Society*, **25** (4). https://doi.org/10.5751/es-12072-250423

299. Allen, C.R. and L.H. Gunderson, 2011: Pathology and failure in the design and implementation of adaptive management. *Journal of Environmental Management*, **92** (5), 1379–1384. https://doi.org/10.1016/j.jenvman.2010.10.063

300. Kochskämper, E., T.M. Koontz, and J. Newig, 2021: Systematic learning in water governance: Insights from five local adaptive management projects for water quality innovation. *Ecology and Society*, **26** (1). https://doi.org/10.5751/es-12080-260122

301. Peat, M., K. Moon, F. Dyer, W. Johnson, and S.J. Nichols, 2017: Creating institutional flexibility for adaptive water management: Insights from two management agencies. *Journal of Environmental Management*, **202**, 188–197. https://doi.org/10.1016/j.jenvman.2017.06.059

302. West, S., R. Beilin, and H. Wagenaar, 2019: Introducing a practice perspective on monitoring for adaptive management. *People and Nature*, **1** (3), 387–405. https://doi.org/10.1002/pan3.10033

303. Walker, B.H., 2012: A commentary on "Resilience and water governance: Adaptive governance in the Columbia River Basin". *Ecology and Society*, **17** (4). https://doi.org/10.5751/es-05422-170429

304. Eshuis, J. and L. Gerrits, 2021: The limited transformational power of adaptive governance: A study of institutionalization and materialization of adaptive governance. *Public Management Review*, **23** (2), 276–296. https://doi.org/10.1080/14719037.2019.1679232

305. Burch, S., A. Gupta, C.Y.A. Inoue, A. Kalfagianni, Å. Persson, A.K. Gerlak, A. Ishii, J. Patterson, J. Pickering, M. Scobie, J. Van der Heijden, J. Vervoort, C. Adler, M. Bloomfield, R. Djalante, J. Dryzek, V. Galaz, C. Gordon, R. Harmon, S. Jinnah, R.E. Kim, L. Olsson, J. Van Leeuwen, V. Ramasar, P. Wapner, and R. Zondervan, 2019: New directions in earth system governance research. *Earth System Governance*, **1**, 100006. https://doi.org/10.1016/j.esg.2019.100006

306. Dewulf, A., T. Karpouzoglou, J. Warner, A. Wesselink, F. Mao, J. Vos, P. Tamas, A.E. Groot, A. Heijmans, F. Ahmed, L. Hoang, S. Vij, and W. Buytaert, 2019: The power to define resilience in social–hydrological systems: Toward a power-sensitive resilience framework. *WIREs Water*, **6** (6), e1377. https://doi.org/10.1002/wat2.1377

307. Koontz, T.M., D. Gupta, P. Mudliar, and P. Ranjan, 2015: Adaptive institutions in social-ecological systems governance: A synthesis framework. *Environmental Science & Policy*, **53**, 139–151. https://doi.org/10.1016/j.envsci.2015.01.003

308. Morrison, T.H., W.N. Adger, K. Brown, M.C. Lemos, D. Huitema, J. Phelps, L. Evans, P. Cohen, A.M. Song, R. Turner, T. Quinn, and T.P. Hughes, 2019: The black box of power in polycentric environmental governance. *Global Environmental Change*, **57**, 101934. https://doi.org/10.1016/j.gloenvcha.2019.101934

309. Fedele, G., C.I. Donatti, C.A. Harvey, L. Hannah, and D.G. Hole, 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, **101**, 116–125. https://doi.org/10.1016/j.envsci.2019.07.001

310. Barnes, M.L., P. Wang, J.E. Cinner, N.A.J. Graham, A.M. Guerrero, L. Jasny, J. Lau, S.R. Sutcliffe, and J. Zamborain-Mason, 2020: Social determinants of adaptive and transformative responses to climate change. *Nature Climate Change*, **10** (9), 823–828. https://doi.org/10.1038/s41558-020-0871-4

311. Wilson, R.S., A. Herziger, M. Hamilton, and J.S. Brooks, 2020: From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nature Climate Change*, **10** (3), 200–208. https://doi.org/10.1038/s41558-020-0691-6

312. Anderegg, W.R.L., L.D.L. Anderegg, K.L. Kerr, and A.T. Trugman, 2019: Widespread drought-induced tree mortality at dry range edges indicates that climate stress exceeds species' compensating mechanisms. *Global Change Biology*, **25** (11), 3793–3802. https://doi.org/10.1111/gcb.14771

313. Ralston, J., W.V. DeLuca, R.E. Feldman, and D.I. King, 2017: Population trends influence species ability to track climate change. *Global Change Biology*, **23** (4), 1390–1399. https://doi.org/10.1111/gcb.13478

314. Pinsky, M.L., R.L. Selden, and Z.J. Kitchel, 2020: Climate-driven shifts in marine species ranges: Scaling from organisms to communities. *Annual Review of Marine Science*, **12** (1), 153–179. https://doi.org/10.1146/annurev-marine-010419-010916

315. Poloczanska, E.S., C.J. Brown, W.J. Sydeman, W. Kiessling, D.S. Schoeman, P.J. Moore, K. Brander, J.F. Bruno, L.B. Buckley, M.T. Burrows, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F. Schwing, S.A. Thompson, and A.J. Richardson, 2013: Global imprint of climate change on marine life. *Nature Climate Change*, **3** (10), 919–925. https://doi.org/10.1038/nclimate1958

316. Kinlan, B.P. and S.D. Gaines, 2003: Propagule dispersal in marine and terrestrial environments: A community perspective. *Ecology*, **84** (8), 2007–2020. https://doi.org/10.1890/01-0622

317. Pinsky, M.L., A.M. Eikeset, D.J. McCauley, J.L. Payne, and J.M. Sunday, 2019: Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature*, **569** (7754), 108–111. https://doi.org/10.1038/s41586-019-1132-4

318. Robinson, L.M., J. Elith, A.J. Hobday, R.G. Pearson, B.E. Kendall, H.P. Possingham, and A.J. Richardson, 2011: Pushing the limits in marine species distribution modelling: Lessons from the land present challenges and opportunities. *Global Ecology and Biogeography*, **20** (6), 789–802. https://doi.org/10.1111/j.1466-8238.2010.00636.x

319. Arietta, A.Z.A., L.K. Freidenburg, M.C. Urban, S.B. Rodrigues, A. Rubinstein, and D.K. Skelly, 2020: Phenological delay despite warming in wood frog *Rana sylvatica* reproductive timing: A 20-year study. *Ecography*, **43** (12), 1791–1800. https://doi.org/10.1111/ecog.05297

320. Johnson, H.E., D.L. Lewis, T.L. Verzuh, C.F. Wallace, R.M. Much, L.K. Willmarth, and S.W. Breck, 2018: Human development and climate affect hibernation in a large carnivore with implications for human–carnivore conflicts. *Journal of Applied Ecology*, **55** (2), 663–672. https://doi.org/10.1111/1365-2664.13021

321. Büntgen, U., A. Piermattei, P.J. Krusic, J. Esper, T. Sparks, and A. Crivellaro, 2022: Plants in the UK flower a month earlier under recent warming. *Proceedings of the Royal Society B: Biological Sciences*, **289** (1968), 20212456. https://doi.org/10.1098/rspb.2021.2456

322. Orgeret, F., A. Thiebault, K.M. Kovacs, C. Lydersen, M.A. Hindell, S.A. Thompson, W.J. Sydeman, and P.A. Pistorius, 2022: Climate change impacts on seabirds and marine mammals: The importance of study duration, thermal tolerance and generation time. *Ecology Letters*, **25** (1), 218–239. https://doi.org/10.1111/ele.13920

323. Maurer, A.S., K. Gross, and S.P. Stapleton, 2022: Beached Sargassum alters sand thermal environments: Implications for incubating sea turtle eggs. *Journal of Experimental Marine Biology and Ecology*, **546**, 151650. https://doi.org/10.1016/j.jembe.2021.151650

324. Ware, M., S.A. Ceriani, J.W. Long, and M.M.P.B. Fuentes, 2021: Exposure of loggerhead sea turtle nests to waves in the Florida Panhandle. *Remote Sensing*, **13** (14), 2654. https://doi.org/10.3390/rs13142654

325. Cohen, J.M., E.L. Sauer, O. Santiago, S. Spencer, and J.R. Rohr, 2020: Divergent impacts of warming weather on wildlife disease risk across climates. *Science*, **370** (6519), eabb1702. https://doi.org/10.1126/science.abb1702

326. Gibb, R., D.W. Redding, K.Q. Chin, C.A. Donnelly, T.M. Blackburn, T. Newbold, and K.E. Jones, 2020: Zoonotic host diversity increases in human-dominated ecosystems. *Nature*, **584** (7821), 398–402. https://doi.org/10.1038/s41586-020-2562-8

327. Fisher, M.C. and T.W.J. Garner, 2020: Chytrid fungi and global amphibian declines. *Nature Reviews Microbiology*, **18** (6), 332–343. https://doi.org/10.1038/s41579-020-0335-x

328. Elith, J. and J.R. Leathwick, 2009: Species distribution models: Ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics*, **40** (1), 677–697. https://doi.org/10.1146/annurev.ecolsys.110308.120159

329. Midgley, G.F., W. Thuiller, and S.I. Higgins, 2007: Ch. 11. Plant species migration as a key uncertainty in predicting future impacts of climate change on ecosystems: Progress and challenges. In: *Terrestrial Ecosystems in a Changing World*. Canadell, J.G., D.E. Pataki, and L.F. Pitelka, Eds. Springer Berlin Heidelberg, Berlin, Heidelberg, 129–137. https://doi.org/10.1007/978-3-540-32730-1_11

330. Moullec, F., N. Barrier, S. Drira, F. Guilhaumon, T. Hattab, M.A. Peck, and Y.-J. Shin, 2022: Using species distribution models only may underestimate climate change impacts on future marine biodiversity. *Ecological Modelling*, **464**, 109826. https://doi.org/10.1016/j.ecolmodel.2021.109826

331. Hoveka, L.N., M. van der Bank, and T.J. Davies, 2022: Winners and losers in a changing climate: How will protected areas conserve red list species under climate change? *Diversity and Distributions*, **28** (4), 782–792. https://doi.org/10.1111/ddi.13488

332. Samplonius, J.M., A. Atkinson, C. Hassall, K. Keogan, S.J. Thackeray, J.J. Assmann, M.D. Burgess, J. Johansson, K.H. Macphie, J.W. Pearce-Higgins, E.G. Simmonds, Ø. Varpe, J.C. Weir, D.Z. Childs, E.F. Cole, F. Daunt, T. Hart, O.T. Lewis, N. Pettorelli, B.C. Sheldon, and A.B. Phillimore, 2021: Strengthening the evidence base for temperature-mediated phenological asynchrony and its impacts. *Nature Ecology & Evolution*, **5** (2), 155–164. https://doi.org/10.1038/s41559-020-01357-0

333. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

334. Winkler, K.J., M.C. Dade, and J.T. Rieb, 2021: Mismatches in the ecosystem services literature—A review of spatial, temporal, and functional-conceptual mismatches. *Current Landscape Ecology Reports*, **6** (2), 23–34. https://doi.org/10.1007/s40823-021-00063-2

335. Heris, M., K.J. Bagstad, C. Rhodes, A. Troy, A. Middel, K.G. Hopkins, and J. Matuszak, 2021: Piloting urban ecosystem accounting for the United States. *Ecosystem Services*, **48**, 101226. https://doi.org/10.1016/j.ecoser.2020.101226

336. Aronson, M.F., C.A. Lepczyk, K.L. Evans, M.A. Goddard, S.B. Lerman, J.S. MacIvor, C.H. Nilon, and T. Vargo, 2017: Biodiversity in the city: Key challenges for urban green space management. *Frontiers in Ecology and the Environment*, **15** (4), 189–196. https://doi.org/10.1002/fee.1480

337. Meerow, S. and J.P. Newell, 2017: Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. *Landscape and Urban Planning*, **159**, 62–75. https://doi.org/10.1016/j.landurbplan.2016.10.005

338. Grabowski, Z.J., T. McPhearson, A.M. Matsler, P. Groffman, and S.T.A. Pickett, 2022: What is green infrastructure? A study of definitions in US city planning. *Frontiers in Ecology and the Environment*, **20** (3), 152–160. https://doi.org/10.1002/fee.2445

339. Hoover, F.-A. and M.E. Hopton, 2019: Developing a framework for stormwater management: Leveraging ancillary benefits from urban greenspace. *Urban Ecosystems*, **22** (6), 1139–1148. https://doi.org/10.1007/s11252-019-00890-6

340. Shriver, R.K., C.M. Andrews, D.S. Pilliod, R.S. Arkle, J.L. Welty, M.J. Germino, M.C. Duniway, D.A. Pyke, and J.B. Bradford, 2018: Adapting management to a changing world: Warm temperatures, dry soil, and interannual variability limit restoration success of a dominant woody shrub in temperate drylands. *Global Change Biology*, **24** (10), 4972–4982. https://doi.org/10.1111/gcb.14374

341. Simonson, W.D., E. Miller, A. Jones, S. García-Rangel, H. Thornton, and C. McOwen, 2021: Enhancing climate change resilience of ecological restoration—A framework for action. *Perspectives in Ecology and Conservation*, **19** (3), 300–310. https://doi.org/10.1016/j.pecon.2021.05.002

342. Hobbs, R.J., 2016: Degraded or just different? Perceptions and value judgements in restoration decisions. *Restoration Ecology*, **24** (2), 153–158. https://doi.org/10.1111/rec.12336

343. Opperman, J.J. and G.E. Galloway, 2022: Nature-based solutions for managing rising flood risk and delivering multiple benefits. *One Earth*, **5** (5), 461–465. https://doi.org/10.1016/j.oneear.2022.04.012

344. Lynham, J., B.S. Halpern, T. Blenckner, T. Essington, J. Estes, M. Hunsicker, C. Kappel, A.K. Salomon, C. Scarborough, K.A. Selkoe, and A. Stier, 2017: Costly stakeholder participation creates inertia in marine ecosystems. *Marine Policy*, **76**, 122–129. https://doi.org/10.1016/j.marpol.2016.11.011

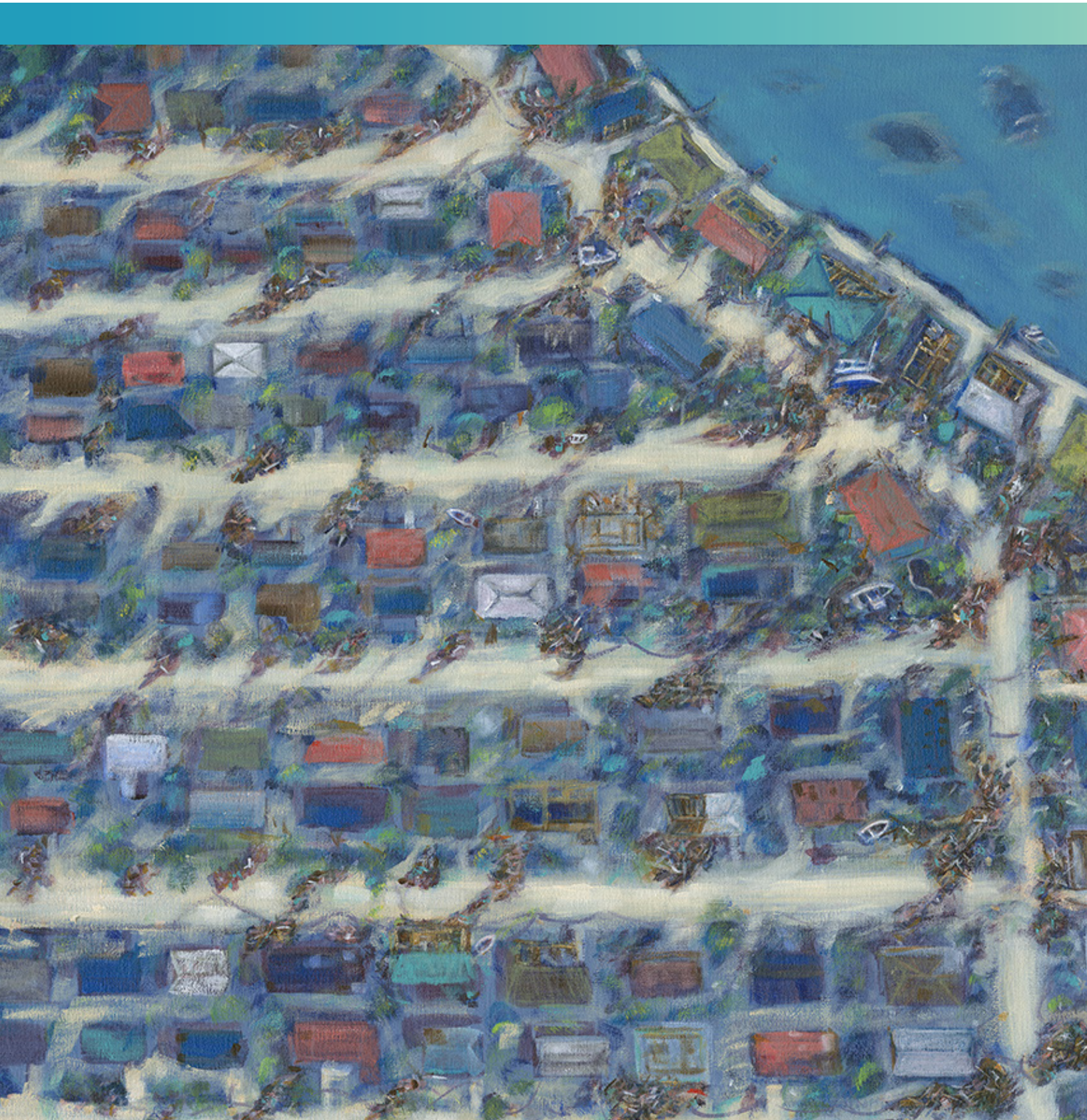
345. Aidoo, F.S., 2021: Architectures of mis/managed retreat: Black land loss to green housing gains. *Journal of Environmental Studies and Sciences*, **11** (3), 451–464. https://doi.org/10.1007/s13412-021-00684-3

346. Heck, S., 2021: Greening the color line: Historicizing water infrastructure redevelopment and environmental justice in the St. Louis metropolitan region. *Journal of Environmental Policy & Planning*, **23** (5), 565–580. https://doi.org/10.1080/1523908x.2021.1888702

347. Buck, H.J., J. Furhman, D.R. Morrow, D.L. Sanchez, and F.M. Wang, 2020: Adaptation and carbon removal. *One Earth*, **3** (4), 425–435. https://doi.org/10.1016/j.oneear.2020.09.008

Fifth National Climate Assessment: Chapter 9

# Coastal Effects



# Chapter 9. Coastal Effects

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# Introduction

Our Nation's coasts support industries, commerce, communities, cultures, traditions, and recreation while also providing iconic landscapes and diverse ecosystem services. Observed sea level rise (SLR) and changes in the frequency and intensity of extreme storms, coupled with changes in land use and land cover that can magnify flood risk, have a significant and demonstrable negative impact on people living and working along the coast. Impacts are expected to worsen in the coming decades as SLR continues to accelerate. Observed and projected trends vary along our Nation's coasts (KM 9.1); therefore, consideration of local and regional trends is important when evaluating impacts (KM 9.2) and adaptation (KM 9.3).[1,2]

The number of people living in coastal areas at risk of SLR inundation (permanent inundation by daily high tides) or surge- or wave-driven flooding (temporary flooding driven by storm events) is in continual flux.[3] Between 1990 and 2020, the number of people living below high tide elevations plus 3.3 feet (1 m) of SLR increased by about 14%–18% to 2.2 million, consistent with continued growth and development.[3] Human modifications to coastal landscapes, such as seawalls and levees, can exacerbate flood risks and erosion[4,5,6] and affect the ability of coastal ecosystems to naturally adapt.[7]

Weather-related disasters continue to increase across US coasts (KMs 2.2, 3.5), with SLR amplifying the flooding and impacts to coastal communities. Between 2000 and 2021, 38 tropical cyclones caused over $1 trillion in losses (in 2022 dollars) and 6,200 deaths.[8] Federal, state, and local actions to reduce these losses are underway, yet progress is slow, and substantial wealth inequities, systemically sustained gaps in resources and capacity, and past injustices continue to disparately impact frontline communities, including Tribes and Indigenous Peoples, rural communities, and lower-income populations (KM 20.1). It is difficult to disentangle the vulnerabilities and consequences associated with climate change from histories and racial inequities that shaped social–environmental systems that exist today.[9] However, climate adaptation efforts that embed equity considerations, support environmental justice, and center the local communities may have the best chance of success, using adaptation strategies that range from protection-in-place to planned relocation.[10,11,12]

Increasing weather-related disasters and SLR also increase impacts on coastal ecosystems and natural shorelines, resulting in gradual (e.g., inland migration of wetlands) to abrupt (e.g., storm erosion of dunes and bluffs) changes that increase flood risks and damages to coastal communities and major infrastructure (e.g., highways, railroads, ports, airports, and other critical infrastructure; KM 12.2). The combined impacts will require fundamental reimagining of the coast. Protection structures can reduce risks on an interim basis; however, many communities and the infrastructure they depend on will need gradual relocation to higher ground, which can provide space for coastal ecosystems to adapt (KM 8.1). In some locations, coordinated and deliberate coastal relocation, implemented equitably, will be essential to reduce future risk to lives and livelihoods (KM 31.1).[13,14,15]

## Key Message 9.1

## Coastal Hazards Are Increasing Due to Accelerating Sea Level Rise and Changing Storm Patterns

The severity and risks of coastal hazards across the Nation are increasing (*very likely*, *high confidence*), driven by accelerating sea level rise and changing storm patterns, resulting in increased flooding, erosion, and rising groundwater tables. Over the next 30 years (2020–2050), coastal sea levels along the contiguous US coasts are expected to rise about 11 inches (28 cm), or as much as the observed rise over the last 100 years (*likely*, *high confidence*). In response, coastal flooding will occur 5–10 times more often by 2050 than 2020 in most locations, with damaging flooding occurring as often as disruptive "high tide flooding" does now if action is not taken (*very likely*, *high confidence*).

### *Accelerating Sea Level Rise*

Global mean sea level is rising at an accelerated rate, with the average rate of about 0.05 ± 0.01 inches per year (1.2 ± 0.2 mm per year) over the pre-satellite era (1901–1990)[16] nearly tripling to 0.13 ± 0.02 inches per year (3.4 ± 0.4 mm per year) during the 30-year satellite era (1993–2022)[17] due to thermal expansion from warming waters and the growing contribution from melting glaciers and ice sheets.[18] Global SLR rates further accelerated to 0.17 inches per year (4.4 mm per year) over the last decade (2013–2022), although this acceleration may include components of natural variability due to the short time period.[19]

To help communities plan for an uncertain future, the US Interagency Sea Level Rise Task Force established five future SLR scenarios that span the range of plausible SLR amounts by 2100 using the latest scientific consensus from the Intergovernmental Panel on Climate Change (IPCC) and other scientific bodies.[2] The five SLR scenarios represent the range on a global scale, with projected SLR amounts in 2100 and scenarios defined as follows:

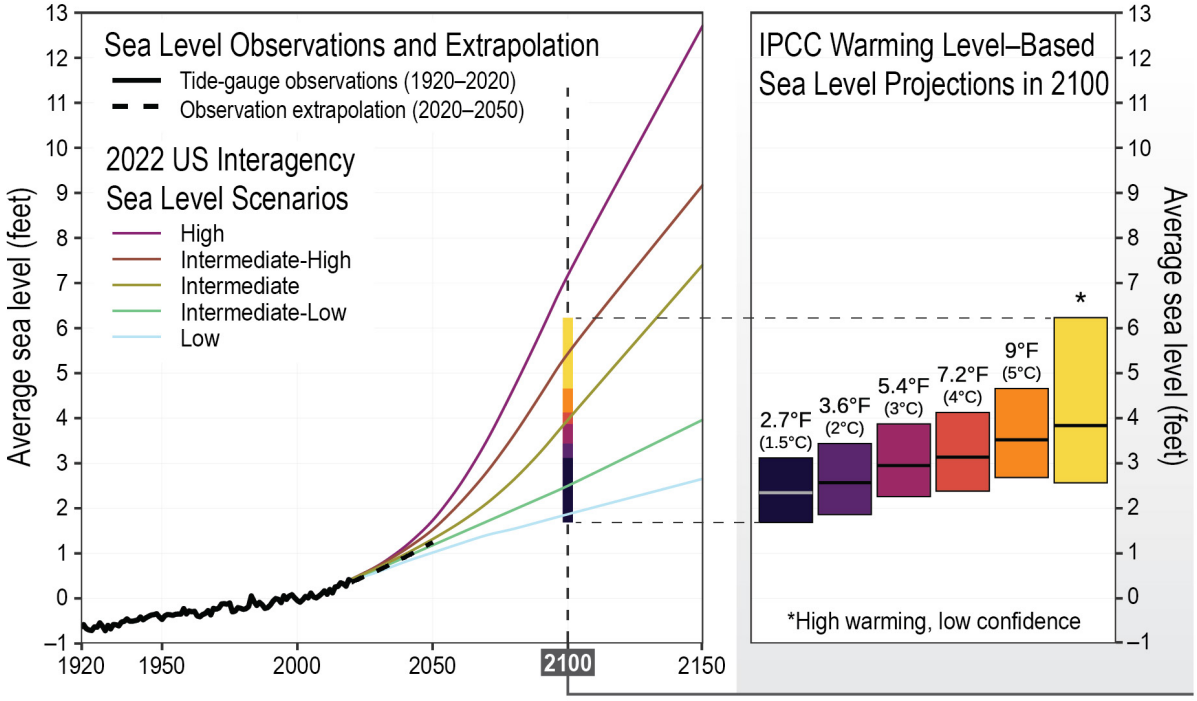
- Low, 1 foot (0.3 m) rise in global mean sea level relative to year 2000 baseline
- Intermediate-Low, 1.6 feet (0.5 m)
- Intermediate, 3.3 feet (1.0 m)
- Intermediate-High, 4.9 feet (1.5 m); and
- High, 6.6 feet (2.0 m) (Figure 9.1)

The SLR scenarios are downscaled to local and regional levels, considering future changes in land elevation, ocean heating and circulation, and Earth's gravitation and rotation from melting of land-based ice. They are constructed directly from the IPCC Sixth Assessment Report (AR6) emissions- and temperature-based projections (App. 3.3)[20] but use consistent framing (e.g., Sweet et al. 2017[21]) to support risk reduction planning.

Sea levels are rising along contiguous US coastlines faster than the global average, with about 11 inches (28 cm; *likely* range of 10–12 inches [25–30 cm]) occurring over the last 100 years (1920–2020) and with about half of this rise (5–6 inches [13–15 cm]) occurring in the last 30 years (1990–2020; Figure 9.1).[2] SLR rates vary across different regions. In the last 30 years, the greatest rise is observed along the US western Gulf Coast (about 9 inches [23 cm]), largely due to high rates of land subsidence[22] from subsurface groundwater and fossil fuel withdrawal.[23] About 6 inches (15 cm) of rise is observed along the northeast and southeast

Atlantic and eastern Gulf Coasts. Lower rates of rise are observed along the Hawaiian and US Caribbean island coastlines (4 inches [10 cm]) and the northwest (2 inches [5 cm]) and southwest (3 inches [8 cm]) Pacific coastlines.[2]

## Accelerating Relative Sea Level Rise in the Contiguous US




**Sea level is projected to continue to increase this century by amounts related to future global warming levels.**

**Figure 9.1.** This figure shows accelerating sea level rise (SLR) trends and SLR scenarios along the contiguous US coastline. It also shows the relationship between projected SLR under different global surface temperature increases in 2100 (KM 2.2). The **left panel** shows observed increasing average sea levels during 1920–2020 (solid black line), an extrapolation out to 2050 based on observed sea levels over 1970–2020 (dashed black line), a range of scenarios describing plausible sea level rise out to 2150 (multicolored lines), and an overlapping stacked bar showing a range of projected changes in 2100 SLR under different levels of global surface temperature increase, based on the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. The **right panel** shows expanded versions of the projections shown in the stacked bar in the left panel. Black lines indicate the median value, the bars show the extent of the *likely* range (17th–83rd percentile) of SLR by 2100, and the associated warming levels are indicated above each bar. The "High warming, low confidence" case (yellow bar) refers to the potential range of rising seas under higher temperatures with rapid ice melt. The lack of overlap in 2100 between the High sea level scenario and the "High warming, low confidence" case in 2100 is not an indication of overestimation but rather a result of how the low-confidence processes are analyzed. Adapted from Sweet et al. 2022.[2]

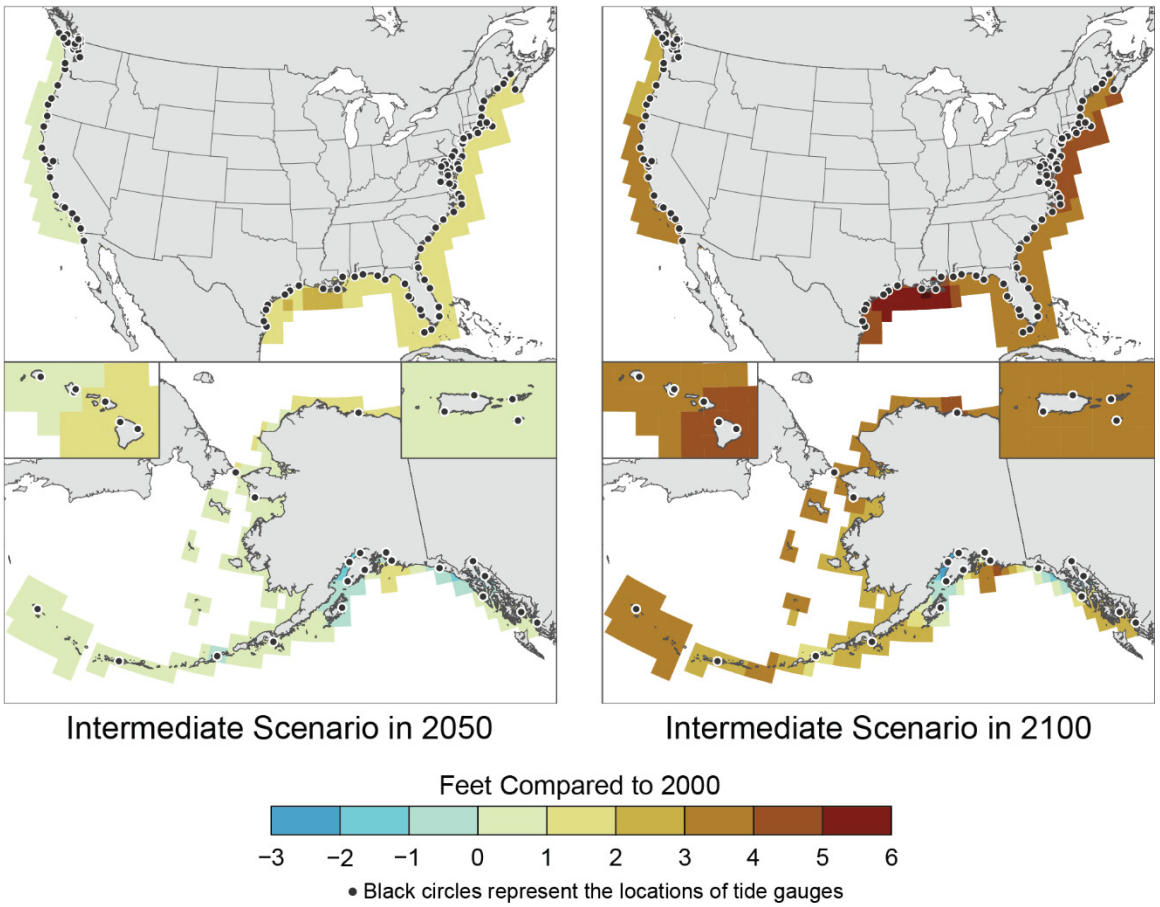
SLR rate suppression and acceleration along the northwest and southwest Pacific coastlines is in part due to oceanographic forcings associated with the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO).[24] Along the Pacific Coast, ENSO and PDO will continue to drive decadal variability in SLR, with rates that are above or below the global average.[24] The current rate remains higher than the global average.[24] Characterizing past (and future) rise for Alaska and the US-Affiliated Pacific Islands is complicated due to tectonic effects that cause both uplift and subsidence. Year-to-year changes associated with natural variability can also change the rates over different analysis periods, such as the 8–12-inch (20–30 cm) variability in sea levels that can occur along the Pacific Coast during different phases of the ENSO.[25,26,27]

Looking toward the future, an 11-inch (28 cm) average rise along the contiguous US coastline is expected by 2050 (relative to 2020, with a *likely* range of 9–13 inches [23–33 cm]; see Table A1.2 in Sweet et al. 2022[2] for 2000 to 2020 offsets) based on an observation-based trajectory of SLR (Figure 9.1). An 11-inch (28 cm) rise by 2050 matches the observed average SLR along the contiguous US coastline over the last 100 years (1920–2020), representing ongoing SLR acceleration that falls between the Intermediate-Low and Intermediate sea level scenarios.[2] By 2050, SLR amounts will continue to vary geographically, with regional differences like those observed in the recent historic record (e.g., 1990–2020). For example, under the Intermediate sea level scenario, which closely aligns with most regional SLR trajectories,[2] SLR is expected to be higher along the Atlantic versus the Pacific Coast and greatest along the western Gulf Coast (Figure 9.2).

Beyond 2050, future global emissions and resultant ocean and atmospheric warming and ice sheet responses will determine future SLR. As of 2021, global temperatures have increased by 2° –2.2°F (1.1°–1.2°C) beyond preindustrial levels (KM 2.1) and are headed for a warming level of about 5.4°F (3°C) by 2100 under the current trajectory,[28] which is consistent with the IPCC AR6 intermediate and high scenarios (SSP2-4.5 and SSP3-7.0). With such warming, it is *likely* that the Intermediate-Low sea level scenario with 2+ feet (0.6+ m) of SLR relative to 2020 levels will be exceeded by 2100, and 3.6+ feet (1.1+ m) will be exceeded by 2150 (App. 3.3; Figure 9.1).[2]

Failing to curb future emissions increases the probability of SLR equivalent to the Intermediate sea level scenario or perhaps even higher, such as the Intermediate-High and High sea level scenarios associated with the IPCC very high scenario (SSP5-8.5) that includes the addition of rapid ice sheet melt or disintegration during this century.[20] The probability of this low-likelihood outcome increases with higher global warming levels.[29] Under the Intermediate to High sea level scenarios, an average SLR of about 3.6–6.9 feet (1.1–2.1 m) along contiguous US coastlines by 2100 and 6.9–12.5 feet (2.1–3.8 m) by 2150 relative to 2020 would occur (Figure 9.1; App. 3.3).[2] Under the Intermediate-High and High sea level scenarios, contributions from the Antarctic ice sheet dominate and reduce overall SLR differences across US regions (KMs 2.1, 2.3).[2] Beyond 2150, global (and US) SLR will continue for millennia due to the long-term effects of warming this century. About 7–33 feet (2–10 meters) of global SLR over the next 2,000 years is *likely* if temperatures warm by 3.6° to 5.4°F (2° to 3°C) above preindustrial levels by 2100, similar to conditions about 125,000 years ago.[20,30]

### Projected Sea Level Rise




**By 2050 and 2100 under the Intermediate sea level scenario, sea level rise is projected to be higher along the Atlantic versus the Pacific Coast and greatest along the western Gulf Coast.**

**Figure 9.2.** The figure shows relative sea level rise along the US coastlines under the Intermediate sea level scenario of the US Interagency Sea Level Rise Task Force[2] for 2050 (**left**) and 2100 (**right**). Relative sea level rise for the contiguous US is shown on the top, and for Alaska, Hawai'i (left insets), and Puerto Rico (right insets) on the bottom. The black dots along the coastline indicate tide-gauge locations used to characterize past SLR. Characterizing past (and future) SLR for Alaska and the US-Affiliated Pacific Islands is complicated due to tectonic effects that cause both uplift and subsidence. Figure credit: NOAA National Ocean Service.

## *Increases in Flooding Frequency Will Continue*

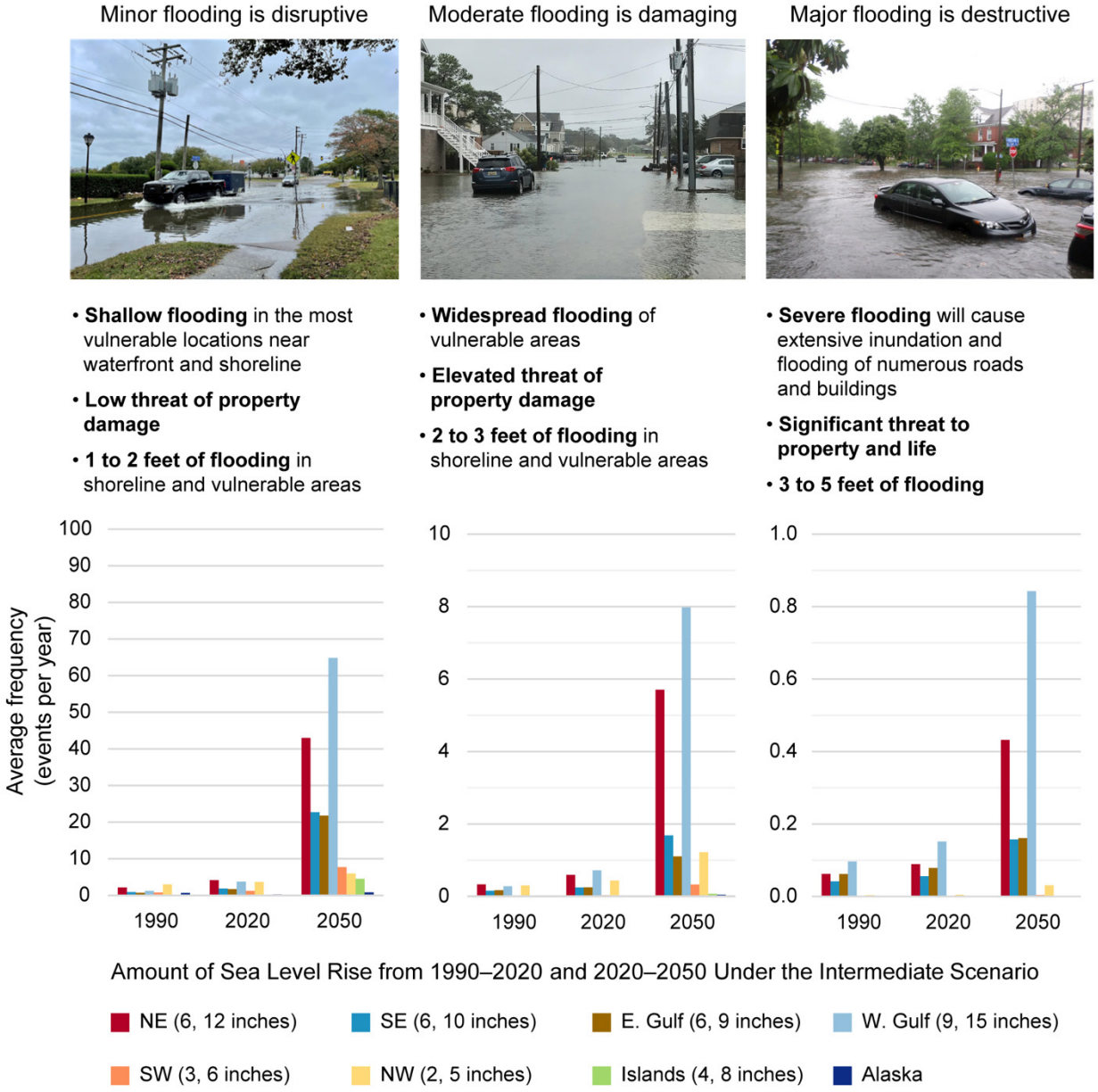
SLR will continue to cause permanent inundation for formerly dry lands and an escalation in the severity (depth, geographic extent, and frequency) of coastal flooding, ranging from powerful storm events to more frequent high tide flooding (HTF). As of 2020, the highest annual frequencies of coastal flooding—defined in a nationally consistent manner as minor (disruptive HTF, about 1.75–2 feet [0.5–0.6 m] above average high tide), moderate (damaging HTF, about 2.75–3 feet [0.8–0.9 m]), and major (destructive HTF, about 4 feet [1.2 m]) impacts[2,31]—are along the northeast Atlantic and western Gulf coastlines (Figure 9.3), due in part to greater exposure to strong storms and wide, shallow continental shelves allowing for higher storm surges.[32]

Annual frequencies of both minor and moderate coastal flooding increased by a factor of 2–3 along most Atlantic and Gulf coastlines between 1990 and 2020 (Figure 9.3). Minor HTF events, which are the most common impact of SLR, occur several times a year with accelerating frequencies (e.g., Sweet et al. 2019,[33] 2020,[34] 2021[35]). A typical HTF event lasts about two days and several high tides.[2] Along the coastlines of

Hawai'i, the US-Affiliated Pacific Islands, and US Caribbean islands, as well as some US Pacific coastlines, SLR is a growing problem. Flood impacts are occurring with much smaller flood heights than those shown in Figure 9.3, including in some cases where water levels are elevated only slightly above high tide.

By 2050 under the Intermediate sea level scenario (Figure 9.1), minor, moderate, and major coastal flood frequencies will all increase by a factor of about 5–10 in many regions relative to 2020 in the absence of adaptation (Figure 9.3). In effect, a flood regime shift would occur; for example, the frequencies of moderate flooding are projected to occur as often as minor, disruptive HTF occurs now (circa 2020). By 2100 under the Intermediate sea level scenario, major flooding would occur almost daily along US coastlines.[2] These increases in flood frequency could be further amplified with higher amounts of SLR, worsening storm conditions, natural climatic variability (e.g., ENSO), or other reasons such as long-term tidal cycles and land subsidence or uplift.[31,36]

## US Regional Average Flood Frequencies




**Minor, moderate, and major coastal flood frequencies will increase by a factor of about 5–10 in many regions of the US relative to 2020 in the absence of adaptation.**

**Figure 9.3.** (**top**) Descriptions of three coastal flood types—minor (disruptive), moderate (damaging), and major (destructive)—provided by NOAA National Weather Service, reflect today's vulnerabilities within coastal communities. (**bottom**) These graphs show annual average frequencies of minor, moderate, and major flooding by region (multicolored bars). The flood frequencies are based on a set of 187 NOAA tide gauges, with 14 in Hawai'i and the US-Affiliated Pacific Islands, 4 in Puerto Rico, and 4 in the US Virgin Islands (collectively shown as Islands). Note that this figure uses the US regions defined in Sweet et al. (2022),[2] which differ from the NCA5 regions: NE = northeast Atlantic, SE = southeast Atlantic, NW = northwest Pacific, SW = southwest Pacific, E. Gulf = eastern Gulf, W. Gulf = western Gulf. Observations are shown for 1990 and 2020, and projections are shown for 2050 under the Intermediate sea level scenario for all US coastal regions. The amount of SLR for each region during 1990–2020 and 2020–2050 under the Intermediate scenario is provided below the graph. The amount of SLR for Alaska is not shown because Alaska's SLR varies along the shoreline due to both tectonic uplift and subsidence; the SLR values for Alaska are shown on Figure 9.2. The annual average frequencies of minor, moderate, and major flooding are projected to increase more in the next 30 years (2020–2050) than they did in the past 30 years (1990–2020) re-

gardless of any future worsening of storm events. In some Atlantic and Gulf Coast regions exposed to hurricanes, more severe and catastrophic coastal flood levels are possible and will become more likely as sea levels rise. Figure credit: NOAA National Ocean Service. Photo credits: (left) City of Norfolk Staff Photographer Andrew Cooper; (center and right) Jeff Orrock, NOAA.

## *Waves, Storminess, and Landscape Variability Amplify Flood Risk*

Climate-driven changes to coastal water levels, including waves, storm surge, river flows, and landscape changes, are important considerations when planning for future flood risk.[37,38,39] Wave-driven water levels, for example, comprise 25%–90% of extreme coastal water levels along exposed US coastlines.[2,40,41] Across most US coasts, many extreme events are increasing in intensity, frequency, and geographic extent (KM 2.2) because of human-caused climate change (KM 3.1). For example, hurricanes are intensifying more rapidly and decaying more slowly, leading to stronger storms extending farther inland with heavier rainfall and higher storm surges, resulting in less time for communities to prepare (KM 2.2). Climate change is also increasing coastal hazards through changes in the frequency, magnitude, and impacts of compound events (Figure 9.3; Focus on Compound Events).[42,43] In the coastal zone, compound flood events are commonly due to the joint occurrence of heavy precipitation, high river flows, elevated groundwater levels, soil saturation, and elevated ocean water levels.[38,44,45]

## Key Message 9.2

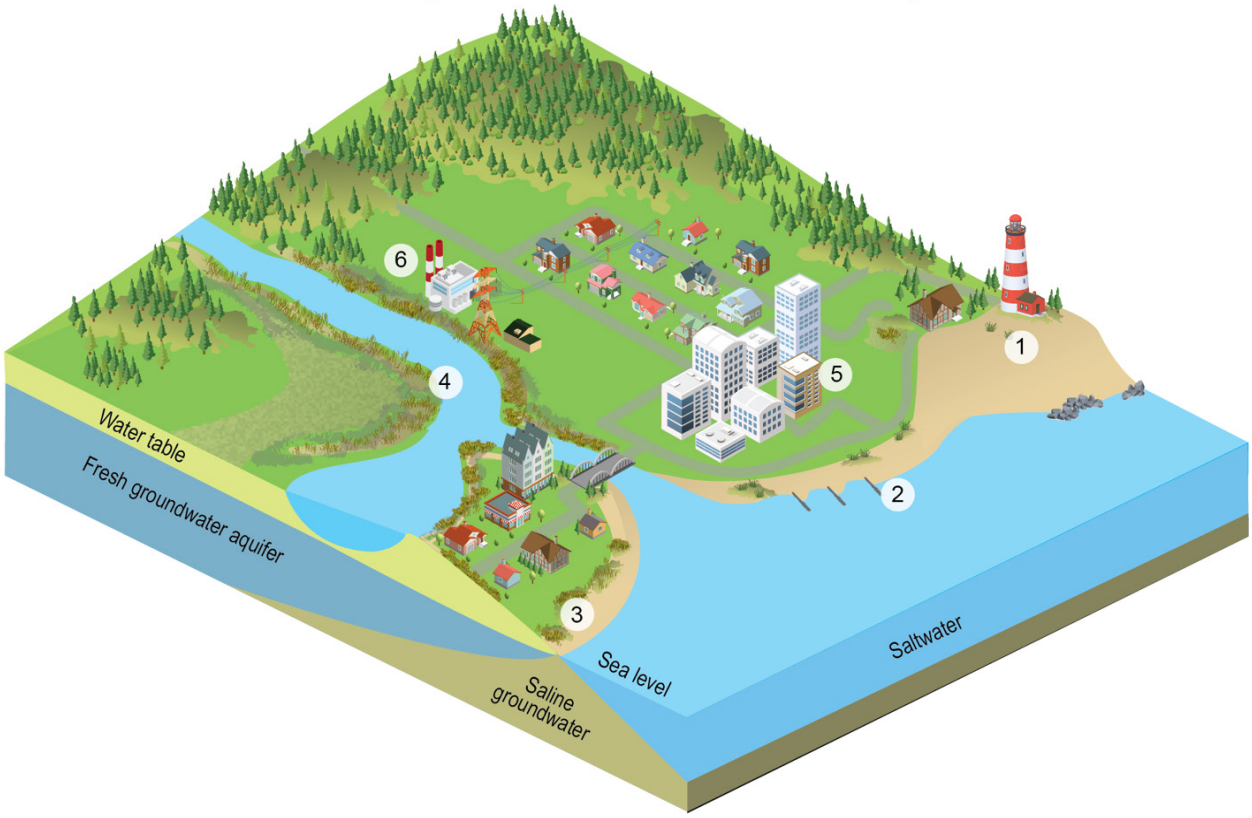
## Coastal Impacts on People and Ecosystems Are Increasing Due to Climate Change

Climate change–driven sea level rise, among other factors, is affecting the resilience of coastal ecosystems and communities (*very likely*, *high confidence*). The impacts of climate change and human modifications to coastal landscapes, such as seawalls, levees, and urban development, are both limiting the capacity of coastal ecosystems to adapt naturally and are compounding the loss of coastal ecosystem services (*very likely*, *high confidence*). Proactive strategies are necessary to avoid degraded quality of life in the coastal zone, as the combination of reduced ecosystem services and damage to the built environment from exacerbated coastal hazards increasingly burdens communities, industries, and cultures (*very likely*, *high confidence*).

On the coast, natural landscapes are intertwined with the cultures, economies, and built infrastructure of humans (Figure 9.4). Coastal landscapes (e.g., beaches, dunes, barrier systems, coastal wetlands, and cliffs) evolve across a range of timescales (from minutes to millennia) in response to physical forcing (e.g., tides, waves, storms, climate variability), as well as biological (e.g., vegetation type and density, ecosystem characteristics) and geological (e.g., sediment flows, tectonics, substrate composition) controls.[46] Climate change is exacerbating coastal hazards, with rising seas and more intense storms leading to increases in both flood risks and shoreline change and erosion (KM 9.1).[47,48,49,50]

Coastal communities face heatwaves, heavy rainfall, landslides, compound flooding, and other climate hazards that are not unique to coastal environments.[14] The health, function, and productivity of coastal ecosystems are also being degraded by stressors from human actions (e.g., development, dredging, wetland infill, sediment diversions). Combined, these threats jeopardize attachment to place,[51] economies, and safety (Figure 9.5).[52,53] Understanding the interactions and interconnections between hazards (KM 9.1), communities, and coastal ecosystems is necessary for taking informed action to mitigate and adapt to climate change (KM 9.3).

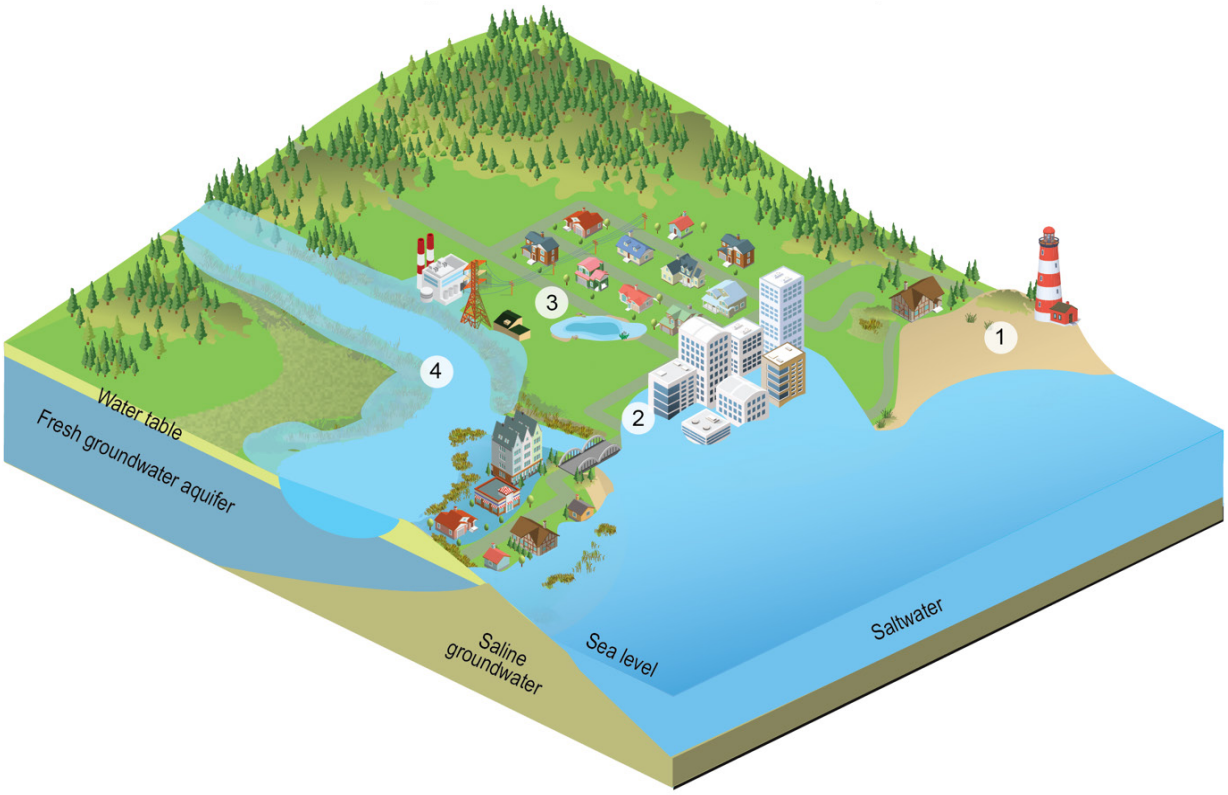
## Existing Conditions in a Coastal Community




**Coastal landscapes and man-made interventions provide economic, cultural, and community protection from existing climate hazards under existing conditions.**

**Figure 9.4.** This hypothetical coastal community shows some of the natural and built environments found in our Nation's actual coastal communities. This community has several types of open coast shorelines, including 1) cliffs, 2) low-lying beaches, and 3) a barrier island. Behind the barrier island is 4) a tidal estuary fringed with marshes. There are two residential neighborhoods, 5) a commercial hub, and 6) an industrial zone that is water dependent. The riprap at the cliff base and beach groins (narrow perpendicular structures extending from the beach into the ocean) provide protection from coastal erosion due to waves. Subsequent figures in this chapter will illustrate the possible impacts of climate change on this community (Figure 9.5) and adaptation strategies to increase its resilience (Figure 9.6). Adapted from Dupigny-Giroux et al. 2018.[54]

### Increasing Hazards in a Coastal Community




**Coastal communities are expected to flood due to rising sea levels and rising groundwater levels.**

**Figure 9.5.** Future climate impacts to our coastal landscapes and communities will be variable. 1) Increased sea level and wave energy will result in shoreline erosion and the collapse of coastal cliffs, which can alter iconic landscapes and damage places of value, including historical or cultural sites. 2) Flooding and wave hazards, including 3) flooding from higher groundwater tables, are anticipated, threatening homes and businesses as well as infrastructure and utilities. 4) Some ecosystems may be able to adapt or migrate to keep pace with future sea levels, and others may become inundated and converted to open water. Adapted from Dupigny-Giroux et al. 2018.[54]

## *Impacts on Communities and People*

Our Nation's coasts underpin substantial sectors of our economy, serving as the entry and exit for goods and services (Focus on Risks to Supply Chains), generating revenue through recreation and tourism, and supporting thriving and diverse fisheries and other water-based industries. Coastal counties contribute $11 trillion annually (in 2022 dollars) in goods and services and employ 58.3 million people.[8] Increasing impacts to coastal systems due to exacerbating hazards will ripple across the US.

As extreme storms intensify and/or the impacts are exacerbated by SLR (KMs 2.2, 3.5), damages are increasing by the billions, with significant damage centered where tropical cyclones (e.g., hurricanes) make landfall[55] and where extratropical cyclones are the more common driver of coastal hazards.[48,56] Extreme storms and more frequent high tide flooding (HTF) bring cascading impacts, including loss of energy accessibility and continuity (KM 5.2); loss of ecosystem services (KMs 8.1, 8.3); impacts to agriculture from flooding and saltwater intrusion into groundwater (KM 30.1); flooding, erosion, and landslide disruptions to transportation (KM 13.1), utilities, infrastructure, emergency services, and teleconnections (KM 12.2); and population migration and displacement (KM 20.3).

Coastal hazard assessments that consider SLR, storm surge, waves, rainfall, and coastal change (e.g., beach and dune change, cliff change) can better depict potential future coastal response and societal impacts.[37,57,58] Compared to assessing only SLR-driven flooding, including these processes greatly expands the floodplain region in the northern Gulf of Mexico[58] and triples the estimated number of people on the Pacific Coast exposed to flooding.[37]

During an extreme event, more ocean water can wash over barrier islands and flow into bays via inlets, enhancing flood risk and amplifying storm surge within inland coastal bays by more than 20%.[59,60,61] Continued population growth and urbanization will expose an ever-increasing number of people to coastal flood risks.[3,62,63,64]

Although extreme storm events make newspaper headlines, SLR brings chronic challenges that could be equally or more damaging over the long term.[2] Coastal groundwater investigations in Pacific Island settings,[65] low-lying atolls,[66] karst aquifers,[67] barrier island systems,[68] and active tectonic margins[69,70] have demonstrated that climate-driven groundwater rise will impact coastal communities and ecosystems due to saltwater intrusion into groundwater sources, more saturated soils, and ponding at the surface comparable in magnitude to SLR-driven overland flooding. Seawater intrusion into coastal aquifers can increase salinity beyond potable levels, endangering access to fresh water for millions of people.[71]

The combination of rising groundwater and HTF in coastal communities will continue to impact stormwater and wastewater infrastructure, including septic systems, and increase the occurrence of urban flooding.[72,73,74,75,76] This could cause public health concerns, such as pollutant discharges into the environment[77] and the spread of environmental infectious diseases (KM 15.1). Additionally, contaminated sites, such as Superfund sites, face increasing exposure to rising groundwater and flood damages, which could lead to future public health and environmental concerns if buried contaminants are mobilized and enter groundwater or river systems (KM 28.2). HTF and rising groundwater will also increase occurrences of roadway flooding, potentially impeding traffic, delaying emergency response efforts, flooding properties, and negatively impacting real estate values and commerce.[78,79,80,81,82] In agricultural areas, rising groundwater and saltwater intrusion in irrigation systems are reducing crop productivity, resulting in barren farmlands in the absence of salt-tolerant crops.[83,84]

The impacts of worsening coastal hazards are not equally distributed across US communities (KM 20.1; Box 20.1).[85,86,87] Disparities in wealth, economic and educational opportunities, infrastructure quality and quantity, and investment in flood risk-reduction measures all contribute to variable physical and socio-economic impacts on coastal residents.[88,89,90] Many Tribal and Indigenous communities face severe impacts from extreme storms, erosion, permafrost thaw, and SLR, with limited resources to support adaptation (KMs 16.1, 29.4, 29.7; Ch. 30). Historic redlining policies forced communities of color into the least valuable, often low-lying lands that have increased flood risks, higher exposure to toxic substances, and more climate change–exacerbated hazards than non-redlined neighborhoods.[91,92,93] Communities that are economically disadvantaged have a higher statistical risk of flood exposure than wealthier communities.[86,87,88] This inequity is further increased because the impact of coastal flooding on individuals and communities is not only based on flood damages but also the ability to pay for the costs of recovery.[85] Decades of limited community inclusion in decision-making and disinvestment in critical infrastructure and community services have generated greater risk to physical and socioeconomic impacts of coastal hazards.[94]

In addition to direct impacts from acute events, chronic impacts are also experienced unequally among coastal residents. Changes in ecosystem services such as fisheries habitats will impact Indigenous practices in which culture and biodiversity are inextricably linked. In the Hawaiian Islands, *loko iʻa* (Hawaiian fishponds) are low-intensity forms of aquaculture that traditionally provided food security, contributing to coastal community resilience (KMs 30.1, 30.5).[95,96] These systems are threatened by SLR, with consequenc-

es on local livelihoods and cultural practices. Other communities, such as subsistence fishers and fisheries-based rural villages, will similarly suffer as negative impacts on coastal fisheries habitat threaten their way of life (KMs 10.1, 10.2).

The steady rise in flood insurance prices reduces home affordability in coastal regions, with many heirs and low-income and moderate-income property owners unable to afford flood insurance (KMs 16.1, 21.5).[97,98] Aside from home affordability, cascading effects such as climate gentrification—when affluent residents move into low-income areas less exposed to climate hazards, displacing the previous residents[99,100,101]—and lack of workforce will continue impacting culture, diversity, and economic productivity in coastal areas.[99,102,103,104]

## Natural Resilience of the Coast Is Changing

For centuries, humans have been reshaping the coast to meet societal needs through urban development, sediment retention and diversion, and coastal defense structures.[105,106,107] These interventions have driven many coastal systems dangerously close to irreversible and profound change (KM 8.1).[108,109] Ecosystem losses due to erosion, more frequent flooding, and coastal squeeze (where human development or natural elevation change limits or prevents inland migration of coastal habitats) will increasingly limit the capacity of coastal landscapes to adapt naturally and diminish their ability to provide valuable ecosystem services (Figure 9.5; KM 8.1).[47,110,111,112,113]

Mangroves and salt marshes, collectively referred to as tidal wetlands, provide culturally and economically essential fisheries habitat and absorb and store floodwaters (Focus on Blue Carbon).[114,115] SLR and increasing coastal hazards (KM 9.1), as well as eutrophication, sediment availability, poor drainage, and coastal squeeze can all drive tidal wetland loss.[116,117] Some tidal wetlands may survive in place due to accretion, while others may migrate upland and convert other ecosystems (e.g., upland habitat, agriculture, and forests) into tidal wetlands.[118,119]

Throughout the US, a net loss of tidal wetlands is expected, but the rate and extent to which the loss occurs will vary significantly by geography and climate change scenario.[120] For example, in Chesapeake Bay,[121] Florida,[122] and New Jersey,[117] a net loss of tidal wetlands is expected. Along the Gulf Coast, mangroves are overtaking salt marshes, reflecting a shift in vegetation dynamics and habitat.[123] Coastal development and steep topography limit inland migration along the Pacific Coast, and tidal wetland conversion to open water and net tidal wetland loss due to SLR appear inevitable.[124]

Barrier islands and reef systems act as a first line of flood defense, absorbing wave impacts as large storms make landfall, thereby reducing flood risk for coastal and inland communities.[125,126,127,128,129] Barrier island and mainland beach systems may migrate landward naturally to keep pace with SLR, or they may be outpaced and narrow and/or flatten depending on their elevation, how frequently storm waves wash over them, sediment supply, and the persistence of vegetation, all of which can be affected by human modifications.[61,130,131,132,133,134,135]

Long-term observations, projections of coastal change and erosion, and improved understanding of complex coastal feedback processes help define the conditions and tipping points that may limit natural adaptation (KM 8.1).[136,137] Climate adaptation that restores natural processes and works with coastal ecosystems and landscapes may reduce flood risks while providing multiple co-benefits, including carbon sequestration (KM 8.1; Focus on Blue Carbon). For example, acquired or restored open-space areas (e.g., undeveloped, agricultural, or park lands) along the coast can provide accommodation space for inland wetland and coastal habitat migration as seas rise.[138,139]

Allowing coastal ecosystems to evolve naturally may negatively impact some communities and wildlife species, such as the reshaping of barrier islands in response to extreme events that can increase inland storm surge (KM 9.1); however, these natural changes may have beneficial impacts for other species and communities through habitat creation and water quality improvements.[50,134] All changes across the landscape have implications for changes to biodiversity via species declines, species range and phenological shifts, disease, and impacts from invasive species (KM 8.2), affecting seagrasses, corals, mangroves, fisheries, shorebirds, and marine mammals (KMs 21.2, 22.1, 23.2, 26.3, 27.3, 28.2, 30.4).

## Key Message 9.3

## Adaptation Reduces Risk and Provides Additional Benefits for Coastal Communities

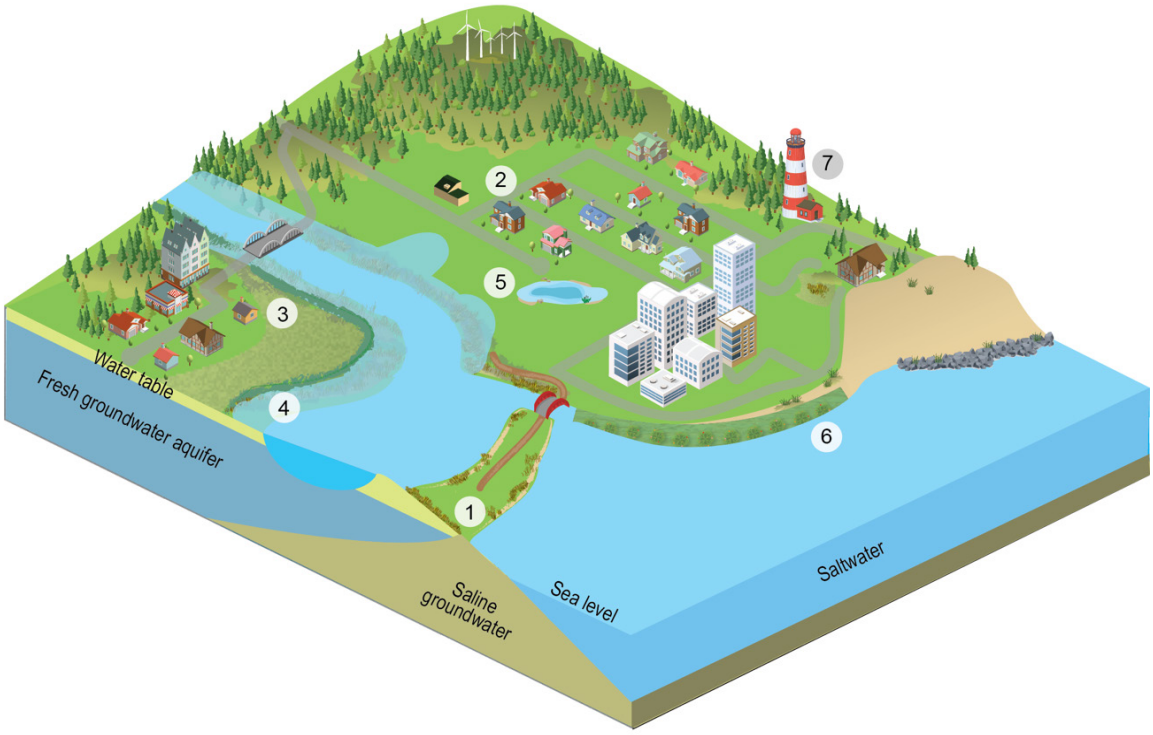
Accelerating sea level rise and climate change will transform the coastal landscape, requiring a new paradigm for how we live with, or adapt to, these changes (*high confidence*). Although incremental in nature, nature-based solutions and planned relocation strategies may help communities adapt to increasing coastal hazards if they are community-led and equity-centered (*medium confidence*). Maintaining cultural and economic connections within coastal communities will require equitable transformative adaptation that addresses systemic interconnections between ecosystems, communities, and governance (*medium confidence*).

Despite projected climate change impacts, coastal communities remain valued places for living and working. Relentless growth in, and enthusiasm for, the coast creates a tension between the need to adapt to climate change and our existing relationships with the coast.[14,140] Although adaptation is occurring in some locations, small-scale and incremental adaptations are not sufficient for the pace and scale of changes that are already occurring (KMs 9.2, 31.1).[13,14,15] Accelerating SLR and increasing coastal hazards (KM 9.1) are affecting larger geographic areas along the coast, expanding the scale and complexity of the adaptation responses and the number and diversity of stakeholders at risk.[13]

Adaptation that includes a broad suite of strategies that address the root causes of coastal vulnerability, consider the needs of diverse stakeholders, center equity (KM 31.2), and reframe societal values and assumptions can lead to transformative and systemic change that can allow coastal communities to thrive and maintain a relationship with the coast (KMs 22.1, 31.3).[141] Example strategies can include updated land-use policies,[142,143] community infrastructure investments, nature-based solutions (NBSs), and planned relocation.[14,144] Individually, these strategies are incremental steps, but when combined in a manner that considers long-term community goals and inclusive and sustained engagement with frontline communities, they can lead to equitable transformative adaptation (Figures 9.6, 22.6, 31.3; Box 9.1; KMs 31.2, 31.3).[14,145]

Transformative adaptation requires fundamental shifts in systems, values, and practices to equitably address the risks of climate change (KM 31.3), including integration of local perspectives, which leads to more equitable distribution of resources.[9] Community-led adaptation actions and NBSs can also enhance a sense of place by recreating lost relationships with the coast or fostering new ones between people and the environment.[14]

## Adaptation Strategies for a Coastal Community




**Timely implementation of adaptation strategies, including planned relocation, can reduce the impacts of climate change on coastal communities.**

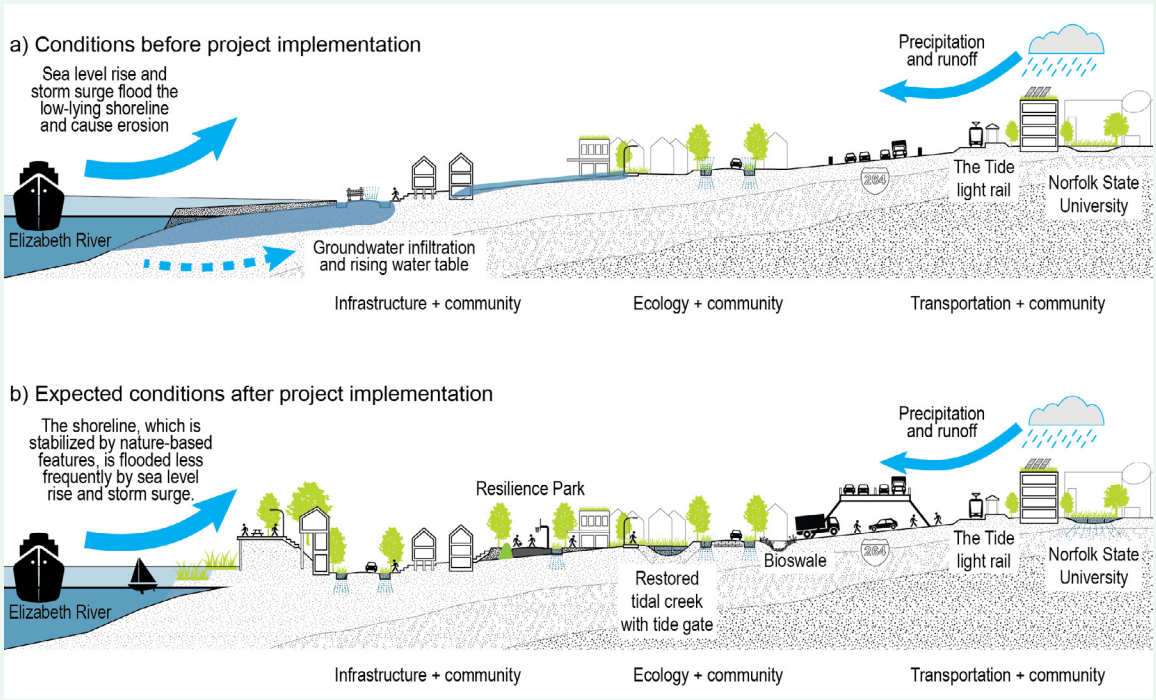
**Figure 9.6.** Many strategies can reduce climate-driven coastal hazards. 1) Critical infrastructure, housing, and businesses can relocate out of harm's way. Retreated lands create space for parks and recreational areas, nature-based solutions (NBSs) for flood risk-reduction, or migration space for coastal ecosystems, while also accommodating rising waters. 2) Relocated communities may move into established communities, or 3) they may create new residential centers. Intentional and equitable stakeholder engagement helps ensure that historic inequities are not perpetuated during relocations. 4) NBSs, such as restoring wetlands, can slow and store rising waters. 5) Housing and structures can be relocated away from rising groundwater tables. 6) Combinations of green and gray infrastructure (hybrid strategies) may be required; for example, a living seawall provides shoreline protection and beneficial habitat for marine organisms. 7) Cultural assets that define a community's character, such as this lighthouse, can be elevated or moved. Adapted from Dupigny-Giroux et al. 2018.[54]

## Box 9.1. On the Road to Adaptation: Norfolk, Virginia

Norfolk, Virginia, home to 245,000 residents and the world's largest naval complex, lies at the mouths of the James and Elizabeth Rivers and Chesapeake Bay. The rate of sea level rise is currently about 0.2 inches (4.7 mm) per year and accelerating. Today, high tide flooding (HTF) occurs 10–15 times annually and by 2050 could occur 85–125 times per year on average.[2,146] Large-scale resilience projects that feature nature-based solutions (NBSs) are under construction as a result of citizen-led strategies that informed the city's land use, regulations, and investments.[147]

The Ohio Creek Watershed Project, funded by a $112 million National Disaster Resilience Competition grant, addresses HTF, storm flooding, and shoreline erosion that caused community isolation and fragmentation (Figure 9.7). The neighborhoods are predominantly Black and include a public housing development and hundreds of homes on the National Historic Register. An extensive community involvement process made sure that residents from the impacted neighborhoods were heard and that societal challenges would be addressed. The project's centerpiece is Resilience Park, including a restored tidal creek and flood berm, wetlands, and NBSs. Surrounding neighborhoods will have accessible roads during HTF events and gain community gathering spaces and places for work and play.

### Present and Future State of the Ohio Creek Watershed




**Strategies that consider long-term community goals and inclusive and sustained engagement with frontline communities can lead to equitable transformative adaptation.**

**Figure 9.7.** By centering the concept of community, neighborhoods will receive shoreline protection to address sea level rise and higher storm surge, updated infrastructure to address rising groundwater and increasing precipitation and runoff, a large gathering space known as Resilience Park, and accessible transportation for people and vehicles. This example of transformative adaptation involves traditional engineering projects and nature-based solutions. Adapted with permission from Waggonner & Ball ©2022.[148]

## Nature-Based Solutions in Coastal Communities

NBSs integrate natural processes with traditional engineering approaches to reduce flood risk while also preserving or enhancing the ecological value of natural landscapes (e.g., maintaining essential habitat for protected species) and providing potential societal, economic, and other co-benefits (Focus on Blue Carbon).[149,150] NBSs can include ecosystem conservation and restoration or recreation of natural processes that reduce flood risks, hybrid solutions (e.g., living shorelines), and the greening of traditional infrastructure (e.g., ecological riprap).[151,152] Although NBSs are effective in reducing temporary flooding resulting from storms, they may provide only modest benefits in preventing permanent inundation from SLR.[149,153] However, when NBSs are paired with planned relocation, protection from flooding and SLR is provided by moving a community out of harm's way while also reestablishing the natural flood risk-reduction benefits of coastal ecosystems.[52]

Mangroves and other coastal wetlands reduce wave energy,[154,155] decrease coastal erosion,[156,157] and provide flood attenuation.[114,158,159] Wetlands helped communities avoid $795.2 million (in 2022 dollars) in direct flood damages during Hurricane Sandy.[127] Beaches and dunes reduce storm surges and absorb wave energy.[160] Coral reefs damp wave energy and provide flood protection for adjacent communities, with an estimated flood risk-reduction benefit of over $2.2 billion annually (in 2022 dollars) in the contiguous US[161,162] and more than $1.1 billion (in 2022 dollars) annually in Hawai'i, Guam, American Sāmoa, the Commonwealth of the Northern Mariana Islands, Florida, Puerto Rico, and the US Virgin Islands.[163]

Hybrid solutions can reduce shoreline erosion[164,165] and enhance the engineering design life and flood risk-reduction performance of traditional infrastructure.[166] Flood risk-reduction benefits of hybrid solutions have been demonstrated across varying hydrodynamic conditions.[165] NBS guidance documents[149,167,168,169] are continually published, and implementation of NBS strategies is increasing. The ability to include adaptive elements in NBSs for future changing conditions[144,170,171] makes them an important component of the adaptation landscape over the coming decades.

## Planned Relocation Strategies in Coastal Communities

Planned relocation is the process of moving individual properties, infrastructure, or whole communities preemptively away from, or in response to, the impacts of natural hazards.[172] Historically, most communities have remained in place post-disaster by adapting or rebuilding using engineered solutions (KM 20.3).[173] However, as climate change impacts increase, adapting and rebuilding in place will become more challenging (KM 31.1). With accelerating SLR, particularly under low-likelihood, high-impact SLR scenarios (Figure 9.1), planned relocation may become more cost effective than adapting in place, with a lower long-term risk of loss of life and property if engineered solutions fail.[174]

In the US, planned relocation generally occurs reactively (i.e., post-disaster) rather than proactively (i.e., relocating at-risk communities before a disaster). For example, targeted buyouts of assets most at risk of future repetitive damage occurred after Hurricane Sandy in Staten Island, New York.[175] Residents and communities have also relocated after natural disasters, such as Isle de Jean Charles, Louisiana;[176] Kivalina, Alaska;[177] and the Quinault Indian Nation (Box 20.1). As planned relocation expands, there is an urgent need to assess lessons learned from past relocations and lean into transformative adaptation that improves community well-being and addresses social, ecological, and intergenerational justice.[178,179]

Proactive planned relocation may become the most viable response for many future coastal communities as SLR continues and coastal lands become submerged.[38,180] However, discussions of planned relocation remain challenging and controversial.[12,174] Impediments include resistance to change;[181] disagreements about when communities and infrastructure may be irrevocably lost and, thus, the appropriate timing for relocation; lack

of community-led decision-making; cost effectiveness compared to defending in place;[174,182] disruptions to community cohesion and social capital;[183,184] and identification of suitable replacement locations.[185]

## *Transformative Adaptation Opportunities in Coastal Communities*

Transformative adaptation that is proactive and intentional and involves fundamental shifts in systems, values, and practices (KM 31.3) provides opportunities to meet the challenges of shifting and receding shorelines. Transformative adaptation along the coast considers aspects such as funding and economic security, alignment of governmental entities, attachment to place and livelihoods, and technical expertise.[52,53]

Intentional and equitable transformative adaptation is an opportunity to redress root causes of inequities and disparate impacts of climate change in coastal communities.[14,15] Achieving this would require sustained funding dedicated to proactive planning, design, and execution.[186] This would prevent reactive strategies that have historically exacerbated inequities and focused resources on wealthy, typically White communities (KM 20.3)[187]—a particular challenge in areas where there are large disparities in wealth and where lower-income homeowners and renters lack affordable flood insurance.[103]

Current adaptation strategies that are increasingly being implemented on the coast could shift toward transformative adaptation if local communities are centered and inequities are transparently addressed (KMs 31.2, 31.3; Figure 31.2). This will require an incremental shift in practice, resulting in additional shifts in systems (e.g., permitting), values (e.g., recognizing and addressing past injustices), and risk tolerance (e.g., increasing comfort in natural shoreline protection over more traditional hardened structures).

# Traceable Accounts

## *Process Description*

This assessment builds upon and amplifies the Key Messages within the "Coastal Effects" chapter of the Fourth National Climate Assessment, as those Key Messages are still relevant, yet they have become even more urgent.[188] The US Interagency Sea Level Rise Task Force's (hereafter "Task Force") report[2] provides clear evidence that sea level rise (SLR) is already accelerating and that current SLR tends are tracking on the Intermediate-Low curve or higher along the Nation's coasts.

Impacts associated SLR and extreme coastal storms are increasing per observations, coastal ecosystems and communities are facing increasing risks, and transformative adaptation grounded with nature-based solutions may provide our best hope to retain a sense of balance between the coasts and our coastal communities. The author team required a depth and breadth of expertise across the Atlantic, Gulf, and Pacific Coasts, as well as the coastlines of Hawai'i and the US-Affiliated Pacific Islands, the US Caribbean, and Alaska; the leading edge of SLR science; the physical processes that shape our coastlines; the systemic inequities that continue to put frontline communities at greatest risk; and the human actions that have altered the coasts and transformed the shoreline to suit societal desires.

Prospective authors were nominated by their respective agencies, universities, organizations, or peers. The chapter lead and federal coordinating lead authors discussed and vetted prospective authors with a goal of creating a cohesive author team committed to bringing their formidable experience and skillsets together to develop this chapter.

This chapter was developed through weekly teleconferences, email exchanges, technical discussions of the relevant evidence base, and expert deliberation by the authors. The author team, along with the US Global Change Research Program, held a public engagement workshop with participants from federal, state, and local agencies; consultants; and interested members of the public. The workshop used innovative approaches and breakout groups that explored what the participants loved most about the coast before diving into the key topics that framed this chapter and the development of the Key Messages.

The urgent need for adaptation, with an emphasis on nature-based solutions and planned relocation, was a clear driver for Key Messages 9.2 and 9.3. Additional literature is required that presents lessons learned and successful implementations, even if at a small scale, to achieve the scale of planned relocation that is expected to be required in the US over the next century.[179] The authors extensively reviewed the literature on transformative adaptation and adaptation that centered equity, community values, and included strong community participation. The concept of transformative adaptation and planned relocation required dialogue across many chapters, with an emphasis on Chapter 20 (Social Systems and Justice) and Chapter 31 (Adaptation) to achieve consistency and portray a sense of urgency for the Nation along these paths.

Consensus on the Key Messages and supporting literature required multiple iterations, discussions with other chapters, and careful review and revisions in response to comments from the public and the National Academies of Sciences, Engineering, and Medicine.

## Key Message 9.1

# Coastal Hazards Are Increasing Due to Accelerating Sea Level Rise and Changing Storm Patterns

### Description of Evidence Base

Multiple lines of evidence, including satellite and tide-gauge observations and model simulations, show that substantial SLR has occurred to date, globally and for the US, as documented and synthesized in the Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (AR6) and the Task Force report on SLR.[2,189] Observations show that SLR is accelerating at global, national, regional, and local levels, and AR6 projections and the sea level scenarios from the Task Force report suggest that these trends are expected to continue over the next several decades and through the end of this century and beyond (see https://sealevel.nasa.gov/data_tools/18).[2,189] Beyond 2150, SLR is expected to continue for the next several thousand years due to the long-term effects of emissions and warming over this past century, irrespective of future emissions occurring after 2100. These lines of evidence are synthesized, and a large body of relevant literature is documented (e.g., Dangendorf et al. 2019;[190] Frederikse et al. 2020;[191] Fox-Kemper et al. 2021;[20] Hamlington et al. 2021;[192] Edwards et al. 2021[193]), in the Task Force report on SLR[2] and IPCC AR6.[189]

An additional body of literature and references therein links this increase in average sea level to a broad range of risks and adverse impacts in the coastal zone. Extreme water levels will continue to rise with SLR, causing deeper, more frequent, more severe, and more widespread flooding (e.g., Sweet et al. 2021,[35] 2022;[2] Taherkhani et al. 2020;[194] Thompson et al. 2021;[36] Vitousek et al. 2017[41]). Observational and model simulation evidence also indicates that many types of extreme events are increasing in intensity, frequency, and geographic extent as a result of human-caused climate change and that hurricanes, in particular, are intensifying and causing heavier rainfall and higher storm surges, all of which compounds these flood risks (see evidence base underlying Key Messages 2.2 and 3.6 and USGCRP 2017[195]). Extreme water levels and flooding lead, in turn, to additional coastal zone impacts (e.g., erosion, damage to property and infrastructure, ecosystem impacts). Compound flooding associated with other coastal storm types (e.g., atmospheric rivers, extratropical cyclones) is also projected to increase with a warming climate.[196,197,198]

A further body of literature documents how population growth, migration, and development trends in the coastal zone have exacerbated societal risks and exposure of populations and the built environment to increasing SLR- and flooding-related hazards.[199,200,201]

### Major Uncertainties and Research Gaps

For near-term impacts (to 2050), uncertainties and research gaps include the impact of natural climate variability on the observation-based trajectories, coastal adaptation, and policy actions to reduce future hazards and improved incorporation of interacting and compounding drivers into projections of coastal water levels and overall coastal flood hazards, such as winds, surge, waves, rising water tables, and extreme rainfall. In addition, more detailed understanding of, and data on, compound flood hazards is a key area of research needed to better understand and communicate flood risks and inform adaptation efforts.

For longer-term impacts (after 2050), major uncertainties and research gaps include improved modeling and observational capabilities to assess long-term global average SLR trajectories as a function of uncertainties in both emissions pathways and the sensitivity of ice sheet dynamical processes to a given level of warming, particularly the "low-confidence" ice sheet processes, as per IPCC AR6.[20] Projections that include these ice sheet processes, particularly under higher-emissions futures, result in substantially higher global average SLR values by the end of this century and beyond. Pathways to such futures include outcomes

such as earlier-than-projected ice shelf disintegration in Antarctica; abrupt, widespread onset of marine ice sheet instability and/or marine ice cliff instability in Antarctica; and faster-than-projected changes in surface-mass balance on Greenland, potentially associated with changes in atmospheric circulation, cloud processes, or albedo changes.[2] Monitoring the sources of ongoing SLR and the processes driving changes in sea level is critical for assessing scenario divergence and tracking the trajectory of observed SLR, particularly during the period when future emissions pathways might increase the risk of triggering these low-confidence processes.

### Description of Confidence and Likelihood

Based on a spatially weighted average of about 100 NOAA tide gauges and following methodologies in Sweet et al. (2022),[2] there is *high confidence* that sea levels along the contiguous US have risen about 11 inches (*likely* range between 10 and 12 inches) on average over the 1920–2020 period, with about 5–6 of those inches occurring since 1990, indicating that sea level rise is accelerating. There is also *high confidence* that the probability of minor, moderate, and major coastal flooding increased by about 2–3 times between 1990 and 2020 (as defined by contemporary NOAA weather-related impact thresholds calibrated to historic NOAA tide-gauge water level heights). Thus, it is *very likely* that the severity and risks of hazards are increasing.

There is *high confidence* and it is *likely* that sea levels will rise about 11 inches (*likely* range of about 9–13 inches) between 2020 and 2050 based on both extrapolating rates and accelerations estimated from historical tide-gauge observations and model projections, with both approaches producing projections within similar ranges. In response to 11 inches of SLR by 2050, there is *high confidence* and it is *very likely* that the probability of minor, moderate, and major coastal flooding will occur 5–10 times more often by 2050 in many regions without additional flood risk-reduction measures, as compared to contemporary standards.

## Key Message 9.2

## Coastal Impacts on People and Ecosystems Are Increasing Due to Climate Change

### Description of Evidence Base

A growing body of literature captures the limited ability of coastal ecosystems to adapt to climate-driven changes, particularly due to human modification. Multiple lines of evidence show that physical changes in the coastal zone in response to climate change are occurring, including upland conversion and marsh expansion,[121,122,202] expansion of mangrove systems,[123] and marsh and beach loss due to erosion and barriers that limit inland migration of these ecosystems.[47,50,110,119,138,203] The consequent loss of ecosystem services, such as storm protection, wetland carbon sequestration, sensitive habitat, and industry, including agriculture, tourism, recreation, and fishing, has been well documented (e.g., Siverd et al. 2020;[204] Weiskopf et al. 2020[205]), and the amplification of these losses via human modifications of the coast are well supported in the peer-reviewed literature.[105,113,206]

With ecosystem loss, exacerbated coastal hazards, and growing coastal populations, increasing damages and costs have been observed (e.g., Bouwer 2019;[207] Hino et al. 2019;[79] Smiley et al. 2022;[208] Al-Attabi et al. 2023[209]), and ongoing health and safety concerns due to increasing flood frequencies, contaminated water supplies, degraded water quality, exposure to toxic substances, and strains on mental health due to the ongoing threat of disasters have been documented (e.g., Coutu 2018;[210] Makwana 2019;[211] Erickson et al. 2019;[212] Gobler 2020;[213] Raker 2022[214]). Additionally, many studies have shown that 1) overburdened, under-resourced, economically disadvantaged, or otherwise vulnerable populations (e.g., children, people with disabilities) face

a greater burden from disasters (e.g., Conzelmann et al. 2022;[215] Raker 2022;[214] Smiley et al. 2022[208]) and are limited in their ability to recover from these impacts, and 2) existing inequities continue to be magnified (e.g., Erman et al. 2020;[216] Griego et al. 2020;[217] Sou et al. 2021;[218] Dundon and Camp 2021;[219] Bento and Elliott 2022[220]). Municipal coastal officials, elected officials, and staff continually document increasing challenges within their communities through participation in professional organizations (e.g., National League of Cities, Association of State Floodplain Managers, regional communities of practice). Specific challenges include the combination of increasing development and land-use pressures and exacerbating coastal hazards that put more homes, businesses, and individuals at risk. Numerous municipalities are installing backflow preventers, documenting high tide flooding, and attempting to manage magnified impacts from rainfall occurring concurrently with high tide flooding and other coastal hazards (e.g., EcoSystems 2014;[221] WSAV 2018;[222] Coutu 2021[223]).

## Major Uncertainties and Research Gaps

Future coastal landscape change is difficult to model and predict broadly in the spatially detailed form required by decision-makers, due to the multitude and complexity of the processes and feedbacks acting within and across different coastal ecosystems.[137,224,225]

National-scale efforts are emerging to assess the risk of losing vital coastal wetland habitats[112,226] and to monitor the daily to annual status of sandy beaches using satellite imagery.[227,228,229] However, monitoring alone cannot save these at-risk ecosystems; improved understanding and ability to model the thresholds and/or tipping points associated with ecosystem loss versus survival are needed broadly to support proactive planning for management of coastal resources and communities.[58,137] Information is needed about when and where saltwater intrusion may occur and its impacts.[69,230,231]

Anticipating and accounting for future human modifications that may reshape the coast and/or affect ecosystem behaviors are areas of considerable uncertainty.[232] Multidisciplinary scenario development can help to explore the physical changes that may occur, how humans may choose to respond to these changes, and the resources that may be available to support these modifications, such as emplacement or removal of gray and green infrastructure, planned relocation, or trade-offs.[233,234] A better understanding of when and in what form humans may take future action can in turn help inform understanding of the landscape response, which can better frame the immediate and longer-term risks to coastal populations in the future.[232,235]

## Description of Confidence and Likelihood

Based on observations and predictive modeling the authors have *high confidence* that the long-term sustainability of our coastal ecosystems and human systems is *very likely* being affected by climate changes, particularly due to land loss. Observations and modeling have also given us *high confidence* that human measures that have historically been used to limit coastal change and have predominantly relied on hard, fixed infrastructure solutions to protect development are *very likely* to make coastal areas less resilient to future change amplified by climate drivers. With this reduction in resilience, numerous studies have shown there is *high confidence* that coastal ecosystems are *very likely* to be limited in their ability to provide the services on which humans depend. There is *high confidence* based on the array of literature and studies available that the loss of these services are *very likely* to require proactive strategies to address significant and cascading impacts on cities, communities, and ways of life in the coastal zone.

## Key Message 9.3

# Adaptation Reduces Risk and Provides Additional Benefits for Coastal Communities

### Description of Evidence Base

Because coastal hazards will continue to worsen and the impacts to the natural and built environment will increase, coastal communities will have to adapt (or continue to adapt) to climate change. Business-as-usual strategies are not expected to be sufficient in the future because they do not address the root causes of vulnerability in coastal communities[9,14,15] nor acknowledge that sea levels will continue to rise beyond typical infrastructure planning time horizons.[141,236]

Consensus is growing to support nature-based solutions (NBSs) and strategies such as planned relocation as essential components of climate adaptation.[149,153,169,237] There is a growing body of literature that demonstrates that NBSs can successfully provide flood risk protection.[115,160,164,165,237] Multiple studies based on laboratory experiments have demonstrated the capacity of NBSs to attenuate wave energy, currents, and storm surges under a range of controlled conditions.[238,239] Additional studies based on field measurements during extreme coastal events have validated these findings within a range of geographical settings and environmental and extreme weather conditions.[154,156,240] Numerical modeling studies have expanded these findings to low-frequency events and a broader range of extreme conditions.[114,161,162] There is growing evidence on the functionality and performance of NBSs for flood risk reduction. This body of literature supports an increasing number of guidelines and practical guidance for NBS planning, design, and implementation.[149,169] State agencies are beginning to require prioritizing NBSs for coastal adaptation, where possible, in lieu of hardened infrastructure.

Planned relocation continues to be a topic of contentious debate in coastal communities, but there is growing evidence that demonstrates openness by communities to include these strategies in long-term planning discussions.[241] This is particularly true if the definition of planned relocation is broadened to include different land-use policy levers that are common planning tools, such as setbacks or easements,[242] as well as discussions and planning that are led by the community.[243]

Transformative adaptation to SLR is possible, in part, due to the array of efforts used to provide meaningful and understandable information to coastal stakeholders. In the coastal zone, stakeholders span a wide array of sectors, grappling with different priorities, timelines, and urgencies that often lead to differing needs. For example, ecologists designing a wetland restoration require probabilistic estimates of near-term SLR, while planners of critical infrastructure need to understand the full suite of possible risks across both the near term and long term to make wise decisions and investments for the communities they serve. The current state of the science and the corresponding guidance on how to make decisions in the face of the knowns and unknowns around rising seas (e.g., The Application Guide for the 2022 SLR Technical Report) are essential indicators that transformative adaptation, inclusive of NBSs and migration, is achievable.[1]

### Major Uncertainties and Research Gaps

Although it is generally understood that riverine flood risk-reduction projects, such as increasing levee heights, could exacerbate flood risks in downstream communities, the potential for a similar deflection of flood risks from one community in coastal environments is less understood. In San Francisco Bay, a modeling study showed that the addition of a levee or seawall to protect one community could increase flood risks elsewhere on the estuarine shoreline.[6] This concept may be important to consider more broadly along the coast, as it intersects with equity considerations if communities with fewer resources to adapt are confronted with increased risks diverted from communities with greater resources.

Despite the growing number of studies investigating and validating the performance of NBSs for flood risk reduction, research gaps remain with respect to uncertainty in flood risk-reduction benefits under a range of future environmental conditions and hazards, given the intrinsic dynamic nature of NBS systems. Specifically, what strategies work in active coastal zones with high wave energy? Furthermore, research is lacking with respect to NBS strategies in extreme environments, especially the Arctic, where traditional vegetation-centric approaches are not practical. This is especially relevant in western Alaska, where communities are experiencing increasing flood hazards and traditional flood protection is extremely costly. While there has been progress on developing standards and guidelines for using NBSs to reduce flood risk,[149,167,168,169] there remains a need for professional engineering organizations and nongovernmental organizations to expand the existing documentation.

Uncertainties and research gaps on planned relocation tend to focus on the process and willingness of communities to relocate: What are the tipping points that encourage a community to adopt community-wide planned relocation? Where should people move to, and are receiving communities prepared to take in increased populations? How does relocation get paid for? How can the psychological barriers to planned relocation be overcome?

There is a lack of literature exploring the governance structures, laws, and policies necessary to support transformative adaptation, including planned relocation. Spanning the gap between adaptation planning and successfully implementing adaptation solutions on the ground requires overcoming governance challenges.[244] Although the number of legal analyses relevant to adaptation is growing, these analyses are still limited in their practical application and scope.[245,246] Research has demonstrated the value of multidirectional policies, laws, and efforts at stimulating climate planning and adaptation, particularly the benefit of top-down laws directing the need to plan and implement adaptation without being overly prescriptive;[53] however, this work is in its early stages. Comprehensive analyses that explore how current policies impede or foster transformative climate adaptation would help to synthesize and identify where improvements could be made within governance structures to support successful adaptation.

There is limited research on the economic and social drivers of, and impediments to, transformative adaptation in coastal communities. Research is also lacking on the social psychology prerequisites needed for successful transformative adaptation. How will a coastal community know when residents are ready to start down the path of transformative adaptation? How can psychological readiness be fostered, including effective communication of future conditions that may compel this sort of action?

Beyond NBSs and planned relocation, many incremental adaptations are well understood in terms of implementation and impact alone. For example, many communities have experience with raising roads, resizing drainage culverts, and building shoreline stabilization structures. However, research that results in effective guidance is lacking for larger measures, such as infrastructure abandonment or relocation and the aggregation of smaller measures. While there is an emerging body of research on this topic for individual actions,[174,247,248] analysis at the community level across a range of adaptation actions and timelines is lacking.

The body of research supporting transformative adaptation is growing; however, much of this research is not tailored for coastal communities. There is a gap in research on the preconditions for, and drivers of, success in coastal communities. Furthermore, there is also a gap in research that assesses the effectiveness of mitigation and adaptation approaches under low-likelihood, high-impact scenarios, given that these approaches necessarily change under extreme SLR scenarios.

## Description of Confidence and Likelihood

Increasing coastal hazards, changing weather patterns, and extreme storms are causing widespread and rapid changes along our Nation's coasts (high confidence). At present, adaptation efforts are most often

incremental in nature and sector-specific (e.g., focused on adapting a wastewater treatment plant or stretch of roadway) as opposed to community-wide in scale (high confidence). As SLR accelerates, exposing greater populations and geographies to coastal hazards, this adaptation approach will become ineffective.

Adaptation responses that move beyond traditional solutions may include nature-based solutions and planned relocation. There is medium confidence that nature-based solutions and planned relocation strategies, when they are community-led and equity-centered, can provide an equitable response to coastal hazards and climate change impacts. There is medium confidence that transformative adaptation that centers the community within the planning, design, and implementation of multi-benefit solutions can better maintain the social, cultural, and economic connections communities require to thrive.

The statements in this Key Message are supported both in the literature cited and in the author team's understanding of the state of the adaptation practice across a wide variety of coastal communities, both in geography and in social systems. This community-focused lens supplements the published literature and allows the authors to reflect the most current consensus on this topic.

# References


1. Collini, R., J. Carter, L. Auermuller, L. Engeman, K. Hintzen, J. Gambill, R. Johnson, I. Miller, C. Schafer, and H. Stiller, 2022: Application Guide for the 2022 Sea Level Rise Technical Report. Mississippi–Alabama Sea Grant Consortium (MASGP-22-028) and Florida Sea Grant (SGEB 88). National Oceanic and Atmospheric Administration, Office for Coastal Management. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html#application-guide

2. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

3. Titus, J.G., 2023: Population in floodplains or close to sea level increased in US but declined in some counties—Especially among black residents. *Environmental Research Letters*, **18** (3), 034001. https://doi.org/10.1088/1748-9326/acadf5

4. Hummel, M.A., R. Griffin, K. Arkema, and A.D. Guerry, 2021: Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (29), e2025961118. https://doi.org/10.1073/pnas.2025961118

5. Nunn, P.D., C. Klöck, and V. Duvat, 2021: Seawalls as maladaptations along island coasts. *Ocean & Coastal Management*, **205**, 105554. https://doi.org/10.1016/j.ocecoaman.2021.105554

6. Wang, R.-Q., M.T. Stacey, L.M.M. Herdman, P.L. Barnard, and L. Erikson, 2018: The influence of sea level rise on the regional interdependence of coastal infrastructure. *Earth's Future*, **6** (5), 677–688. https://doi.org/10.1002/2017ef000742

7. Sahavacharin, A., P. Sompongchaiyakul, and D. Thaitakoo, 2022: The effects of land-based change on coastal ecosystems. *Landscape and Ecological Engineering*, **18** (3), 351–366. https://doi.org/10.1007/s11355-022-00505-x

8. NCEI, 2022: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

9. Hardy, R.D., R.A. Milligan, and N. Heynen, 2017: Racial coastal formation: The environmental injustice of colorblind adaptation planning for sea-level rise. *Geoforum*, **87**, 62–72. https://doi.org/10.1016/j.geoforum.2017.10.005

10. Green, K.M., J.C. Selgrath, T.H. Frawley, W.K. Oestreich, E.J. Mansfield, J. Urteaga, S.S. Swanson, F.N. Santana, S.J. Green, J. Naggea, and L.B. Crowder, 2021: How adaptive capacity shapes the Adapt, React, Cope response to climate impacts: Insights from small-scale fisheries. *Climatic Change*, **164** (1), 15. https://doi.org/10.1007/s10584-021-02965-w

11. Oestreich, W.K., T.H. Frawley, E.J. Mansfield, K.M. Green, S.J. Green, J. Naggea, J.C. Selgrath, S.S. Swanson, J. Urteaga, T.D. White, and L.B. Crowder, 2019: Ch. 26. The impact of environmental change on small-scale fishing communities: Moving beyond adaptive capacity to community response. In: *Predicting Future Oceans*. Cisneros-Montemayor, A.M., W.W.L. Cheung, and Y. Ota, Eds. Elsevier, 271–282. https://doi.org/10.1016/b978-0-12-817945-1.00027-7

12. Siders, A.R., I. Ajibade, and D. Casagrande, 2021: Transformative potential of managed retreat as climate adaptation. *Current Opinion in Environmental Sustainability*, **50**, 272–280. https://doi.org/10.1016/j.cosust.2021.06.007

13. Fedele, G., C.I. Donatti, C.A. Harvey, L. Hannah, and D.G. Hole, 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, **101**, 116–125. https://doi.org/10.1016/j.envsci.2019.07.001

14. Kuhl, L., M.F. Rahman, S. McCraine, D. Krause, M.F. Hossain, A.V. Bahadur, and S. Huq, 2021: Transformational adaptation in the context of coastal cities. *Annual Review of Environment and Resources*, **46** (1), 449–479. https://doi.org/10.1146/annurev-environ-012420-045211

15. Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372** (6549), 8054. https://doi.org/10.1126/science.abc8054

16. Hay, C.C., E. Morrow, R.E. Kopp, and J.X. Mitrovica, 2015: Probabilistic reanalysis of twentieth-century sea-level rise. *Nature*, **517** (7535), 481–484. https://doi.org/10.1038/nature14093

17. Beckley, B., X. Yang, N.P. Zelensky, S.A. Holmes, F.G. Lemoine, R.D. Ray, G.T. Mitchum, S. Desai, and S.T. Brown. 2021: Global Mean Sea Level Trend from Integrated Multi-Mission Ocean Altimeters TOPEX/Poseidon, Jason-1, OSTM/Jason-2, and Jason-3 Version 5.1. NASA Goddard Space Flight Center. https://doi.org/10.5067/gmslm-tj151

18. Thompson, P.R., M.J. Widlansky, E. Leuliette, D.P. Chambers, W. Sweet, B.D. Hamlington, S. Jevrejeva, M.A. Merrifield, G.T. Mitchum, and R.S. Nerem, 2022: Sea level variability and change in [State of the Climate in 2021]. *Bulletin of the American Meteorological Society*, **103** (8), S168–S172. https://doi.org/10.1175/2022bamsstateoftheclimate.1

19. Guérou, A., B. Meyssignac, P. Prandi, M. Ablain, A. Ribes, and F. Bignalet-Cazalet, 2023: Current observed global mean sea level rise and acceleration estimated from satellite altimetry and the associated measurement uncertainty. *Ocean Science*, **19** (2), 431–451. https://doi.org/10.5194/os-19-431-2023

20. Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ch. 9. Ocean, cryosphere and sea level change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1211–1362. https://doi.org/10.1017/9781009157896.011

21. Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas, 2017: Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 75 pp. https://repository.library.noaa.gov/view/noaa/18399

22. Dokka, R.K., 2011: The role of deep processes in late 20th century subsidence of New Orleans and coastal areas of southern Louisiana and Mississippi. *Journal of Geophysical Research: Solid Earth*, **116** (B6). https://doi.org/10.1029/2010jb008008

23. Kolker, A.S., M.A. Allison, and S. Hameed, 2011: An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. *Geophysical Research Letters*, **38** (21). https://doi.org/10.1029/2011gl049458

24. Hamlington, B.D., T. Frederikse, P.R. Thompson, J.K. Willis, R.S. Nerem, and J.T. Fasullo, 2021: Past, present, and future Pacific sea-level change. *Earth's Future*, **9** (4), e2020EF001839. https://doi.org/10.1029/2020ef001839

25. Barnard, P.L., D. Hoover, D.M. Hubbard, A. Snyder, B.C. Ludka, J. Allan, G.M. Kaminsky, P. Ruggiero, T.W. Gallien, L. Gabel, D. McCandless, H.M. Weiner, N. Cohn, D.L. Anderson, and K.A. Serafin, 2017: Extreme oceanographic forcing and coastal response due to the 2015–2016 El Niño. *Nature Communications*, **8**, 14365. https://doi.org/10.1038/ncomms14365

26. Hamlington, B.D., R.R. Leben, K.Y. Kim, R.S. Nerem, L.P. Atkinson, and P.R. Thompson, 2015: The effect of the El Niño–Southern Oscillation on U.S. regional and coastal sea level. *Journal of Geophysical Research Oceans*, **120** (6), 3970–3986. https://doi.org/10.1002/2014jc010602

27. Wolter, K., 1987: The Southern Oscillation in surface circulation and climate over the tropical Atlantic, eastern Pacific, and Indian Oceans as captured by cluster analysis. *Journal of Applied Meteorology and Climatology*, **26** (4), 540–558. DOI:10.1175/1520-0450(1987)026<0540:tsoisc>2.0.co;2. https://journals.ametsoc.org/view/journals/apme/26/4/1520-0450_1987_026_0540_tsoisc_2_0_co_2.xml

28. Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G.P. Peters, A. Rao, S. Robertson, A.M. Sebbit, J. Steinberger, M. Tavoni, and D.P. van Vuuren, 2022: Ch. 3. Mitigation pathways compatible with long-term goals. In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A.A. Khourdajie, R.v. Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 295–408. https://doi.org/10.1017/9781009157926.005

29. IPCC, 2023: Summary for policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Lee, H. and J. Romero, Eds. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 1-34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

30. Kopp, R.E., F.J. Simons, J.X. Mitrovica, A.C. Maloof, and M. Oppenheimer, 2009: Probabilistic assessment of sea level during the last interglacial stage. *Nature*, **462** (7275), 863–867. https://doi.org/10.1038/nature08686

31. Sweet, W., G. Dusek, J.T.B. Obeysekera, and J.J. Marra, 2018: Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold. NOAA Technical Report NOS CO-OPS 086. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD. https://doi.org/10.7289/v5/tr-nos-coops-086

32. Tebaldi, C., B.H. Strauss, and C.E. Zervas, 2012: Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters*, **7** (1), 014032. https://doi.org/10.1088/1748-9326/7/1/014032

33. Sweet, W., G. Dusek, D. Marcy, G. Carbin, and J. Marra, 2019: 2018 State of U.S. High Tide Flooding with a 2019 Outlook. NOAA Technical Report NOS CO-OPS 090. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD. https://repository.library.noaa.gov/view/noaa/20691

34. Sweet, W., G. Dusek, G. Carbin, J. Marra, D. Marcy, and S. Simon, 2020: 2019 State of U.S. High Tide Flooding with a 2020 Outlook. NOAA Technical Report NOS CO-OPS 092. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD. https://repository.library.noaa.gov/view/noaa/25241

35. Sweet, W., S. Simon, G. Dusek, D. Marcy, W. Brooks, M. Pendleton, and J. Marra, 2021: 2021 State of High Tide Flooding and Annual Outlook. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD. https://tidesandcurrents.noaa.gov/publications/2021_State_of_High_Tide_Flooding_and_Annual_Outlook_Final.pdf

36. Thompson, P.R., M.J. Widlansky, B.D. Hamlington, M.A. Merrifield, J.J. Marra, G.T. Mitchum, and W. Sweet, 2021: Rapid increases and extreme months in projections of United States high-tide flooding. *Nature Climate Change*, **11** (7), 584–590. https://doi.org/10.1038/s41558-021-01077-8

37. Barnard, P.L., L.H. Erikson, A.C. Foxgrover, J.A.F. Hart, P. Limber, A.C. O'Neill, M. van Ormondt, S. Vitousek, N. Wood, M.K. Hayden, and J.M. Jones, 2019: Dynamic flood modeling essential to assess the coastal impacts of climate change. *Scientific Reports*, **9** (1), 4309. https://doi.org/10.1038/s41598-019-40742-z

38. Magnan, A.K., M. Oppenheimer, M. Garschagen, M.K. Buchanan, V.K.E. Duvat, D.L. Forbes, J.D. Ford, E. Lambert, J. Petzold, F.G. Renaud, Z. Sebesvari, R.S.W. van de Wal, J. Hinkel, and H.-O. Pörtner, 2022: Sea level rise risks and societal adaptation benefits in low-lying coastal areas. *Scientific Reports*, **12** (1), 10677. https://doi.org/10.1038/s41598-022-14303-w

39. Toimil, A., M. Álvarez-Cuesta, and I.J. Losada, 2023: Neglecting the effect of long- and short-term erosion can lead to spurious coastal flood risk projections and maladaptation. *Coastal Engineering*, **179**, 104248. https://doi.org/10.1016/j.coastaleng.2022.104248

40. Stockdon, H.F., R.A. Holman, P.A. Howd, and A.H. Sallenger Jr., 2006: Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, **53** (7), 573–588. https://doi.org/10.1016/j.coastaleng.2005.12.005

41. Vitousek, S., P.L. Barnard, C.H. Fletcher, N. Frazer, L. Erikson, and C.D. Storlazzi, 2017: Doubling of coastal flooding frequency within decades due to sea-level rise. *Scientific Reports*, **7** (1), 1399. https://doi.org/10.1038/s41598-017-01362-7

42. Wahl, T., S. Jain, J. Bender, S.D. Meyers, and M.E. Luther, 2015: Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change*, **5** (12), 1093–1097. https://doi.org/10.1038/nclimate2736

43. Zscheischler, J., S. Westra, B.J.J.M. van den Hurk, S.I. Seneviratne, P.J. Ward, A. Pitman, A. AghaKouchak, D.N. Bresch, M. Leonard, T. Wahl, and X. Zhang, 2018: Future climate risk from compound events. *Nature Climate Change*, **8** (6), 469–477. https://doi.org/10.1038/s41558-018-0156-3

44. Feng, D., Z. Tan, D. Engwirda, C. Liao, D. Xu, G. Bisht, T. Zhou, H.Y. Li, and L.R. Leung, 2022: Investigating coastal backwater effects and flooding in the coastal zone using a global river transport model on an unstructured mesh. *Hydrology and Earth System Sciences*, **26** (21), 5473–5491. https://doi.org/10.5194/hess-26-5473-2022

45. Xu, K., C. Wang, and L. Bin, 2023: Compound flood models in coastal areas: A review of methods and uncertainty analysis. *Natural Hazards*, **116** (1), 469–496. https://doi.org/10.1007/s11069-022-05683-3

46. Davidson-Arnott, R., B. Bauer, and C. Houser, 2019: *Introduction to Coastal Processes and Geomorphology*, 2nd ed. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/9781108546126

47. Lentz, E.E., S.L. Zeigler, E.R. Thieler, and N.G. Plant, 2021: Probabilistic patterns of inundation and biogeomorphic changes due to sea-level rise along the northeastern U.S. Atlantic coast. *Landscape Ecology*, **36** (1), 223–241. https://doi.org/10.1007/s10980-020-01136-z

48. Shope, J.B., L.H. Erikson, P.L. Barnard, C.D. Storlazzi, K. Serafin, K. Doran, H. Stockdon, B. Reguero, F. Mendez, S. Castanedo, A. Cid, L. Cagigal, and P. Ruggiero, 2022: Characterizing storm-induced coastal change hazards along the United States West Coast. *Scientific Data*, **9** (1), 224. https://doi.org/10.1038/s41597-022-01313-6

49. Vitousek, S., P.L. Barnard, and P. Limber, 2017: Can beaches survive climate change? *Journal of Geophysical Research: Earth Surface*, **122** (4), 1060–1067. https://doi.org/10.1002/2017JF004308

50. Zeigler, S.L., B.T. Gutierrez, E.E. Lentz, N.G. Plant, E.J. Sturdivant, and K.S. Doran, 2022: Predicted sea-level rise-driven biogeomorphological changes on Fire Island, New York: Implications for people and plovers. *Earth's Future*, **10** (4), e2021EF002436. https://doi.org/10.1029/2021ef002436

51. Brown, B.B., I. Altman, and C.M. Werner, 2012: Place attachment. In: *International Encyclopedia of Housing and Home*. Smith, S.J., Ed. Elsevier, San Diego, CA, 183–188. https://doi.org/10.1016/B978-0-08-047163-1.00543-9

52. Bongarts Lebbe, T., H. Rey-Valette, É. Chaumillon, G. Camus, R. Almar, A. Cazenave, J. Claudet, N. Rocle, C. Meur-Férec, F. Viard, D. Mercier, C. Dupuy, F. Ménard, B.A. Rossel, L. Mullineaux, M.-A. Sicre, A. Zivian, F. Gaill, and A. Euzen, 2021: Designing coastal adaptation strategies to tackle sea level rise. *Frontiers in Marine Science*, **8**, 740602. https://doi.org/10.3389/fmars.2021.740602

53. Holmes, T.J. and W.H. Butler, 2021: Implementing a mandate to plan for sea level rise: Top-down, bottom-up, and middle-out actions in the Tampa Bay region. *Journal of Environmental Planning and Management*, **64** (12), 2214–2232. https://doi.org/10.1080/09640568.2020.1865885

54. Dupigny-Giroux, L.A., E.L. Mecray, M.D. Lemcke-Stampone, G.A. Hodgkins, E.E. Lentz, K.E. Mills, E.D. Lane, R. Miller, D.Y. Hollinger, W.D. Solecki, G.A. Wellenius, P.E. Sheffield, A.B. MacDonald, and C. Caldwell, 2018: Ch. 18. Northeast. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 669–742. https://doi.org/10.7930/nca4.2018.ch18

55. Gori, A., N. Lin, D. Xi, and K. Emanuel, 2022: Tropical cyclone climatology change greatly exacerbates US extreme rainfall–surge hazard. *Nature Climate Change*, **12** (2), 171–178. https://doi.org/10.1038/s41558-021-01272-7

56. Dacre, H.F. and J.G. Pinto, 2020: Serial clustering of extratropical cyclones: A review of where, when and why it occurs. *npj Climate and Atmospheric Science*, **3** (1), 48. https://doi.org/10.1038/s41612-020-00152-9

57. Bilskie, M.V., S.C. Hagen, S.C. Medeiros, and D.L. Passeri, 2014: Dynamics of sea level rise and coastal flooding on a changing landscape. *Geophysical Research Letters*, **41** (3), 927–934. https://doi.org/10.1002/2013gl058759

58. Passeri, D.L., S.C. Hagen, S.C. Medeiros, M.V. Bilskie, K. Alizad, and D. Wang, 2015: The dynamic effects of sea level rise on low-gradient coastal landscapes: A review. *Earth's Future*, **3** (6), 159–181. https://doi.org/10.1002/2015ef000298

59. Bilskie, M.V., S.C. Hagen, K. Alizad, S.C. Medeiros, D.L. Passeri, H.F. Needham, and A. Cox, 2016: Dynamic simulation and numerical analysis of hurricane storm surge under sea level rise with geomorphologic changes along the northern Gulf of Mexico. *Earth's Future*, **4** (5), 177–193. https://doi.org/10.1002/2015ef000347

60. Passeri, D.L., M.V. Bilskie, N.G. Plant, J.W. Long, and S.C. Hagen, 2018: Dynamic modeling of barrier island response to hurricane storm surge under future sea level rise. *Climatic Change*, **149** (3), 413–425. https://doi.org/10.1007/s10584-018-2245-8

61. Passeri, D.L., S.C. Hagen, M.V. Bilskie, and S.C. Medeiros, 2015: On the significance of incorporating shoreline changes for evaluating coastal hydrodynamics under sea level rise scenarios. *Natural Hazards*, **75** (2), 1599–1617. https://doi.org/10.1007/s11069-014-1386-y

62. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

63. Helderop, E. and T.H. Grubesic, 2019: Social, geomorphic, and climatic factors driving U.S. coastal city vulnerability to storm surge flooding. *Ocean & Coastal Management*, **181**, 104902. https://doi.org/10.1016/j.ocecoaman.2019.104902

64. Neumann, B., A.T. Vafeidis, J. Zimmermann, and R.J. Nicholls, 2015: Future coastal population growth and exposure to sea-level rise and coastal flooding—A global assessment. *PLoS ONE*, **10** (3), e0118571. https://doi.org/10.1371/journal.pone.0118571

65. Rotzoll, K. and C.H. Fletcher, 2013: Assessment of groundwater inundation as a consequence of sea-level rise. *Nature Climate Change*, **3** (5), 477–481. https://doi.org/10.1038/nclimate1725

66. Storlazzi, C.D., S.B. Gingerich, A. van Dongeren, O.M. Cheriton, P.W. Swarzenski, E. Quataert, C.I. Voss, D.W. Field, H. Annamalai, G.A. Piniak, and R. McCall, 2018: Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, **4** (4), 9741. https://doi.org/10.1126/sciadv.aap9741

67. Sukop, M.C., M. Rogers, G. Guannel, J.M. Infanti, and K. Hagemann, 2018: High temporal resolution modeling of the impact of rain, tides, and sea level rise on water table flooding in the Arch Creek Basin, Miami-Dade County Florida USA. *Science of The Total Environment*, **616–617**, 1668–1688. https://doi.org/10.1016/j.scitotenv.2017.10.170

68. Masterson, J.P., M.N. Fienen, E.R. Thieler, D.B. Gesch, B.T. Gutierrez, and N.G. Plant, 2014: Effects of sea-level rise on barrier island groundwater system dynamics—Ecohydrological implications. *Ecohydrology*, **7** (3), 1064–1071. https://doi.org/10.1002/eco.1442

69. Befus, K.M., P.L. Barnard, D.J. Hoover, J.A. Finzi Hart, and C.I. Voss, 2020: Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nature Climate Change*, **10** (10), 946–952. https://doi.org/10.1038/s41558-020-0874-1

70. Plane, E., K. Hill, and C. May, 2019: A rapid assessment method to identify potential groundwater flooding hotspots as sea levels rise in coastal cities. *Water*, **11** (11), 2228. https://doi.org/10.3390/w11112228

71. Jasechko, S., D. Perrone, H. Seybold, Y. Fan, and J.W. Kirchner, 2020: Groundwater level observations in 250,000 coastal US wells reveal scope of potential seawater intrusion. *Nature Communications*, **11** (1), 3229. https://doi.org/10.1038/s41467-020-17038-2

72. Cox, A.H., G.W. Loomis, and J.A. Amador, 2019: Preliminary evidence that rising groundwater tables threaten coastal septic systems. *Journal of Sustainable Water in the Built Environment*, **5** (4), 04019007. https://doi.org/10.1061/jswbay.0000887

73. Gold, A.C., C.M. Brown, S.P. Thompson, and M.F. Piehler, 2022: Inundation of stormwater infrastructure is common and increases risk of flooding in coastal urban areas along the US Atlantic coast. *Earth's Future*, **10** (3), e2021EF002139. https://doi.org/10.1029/2021ef002139

74. Hughes, J., K. Cowper-Heays, E. Olesson, R. Bell, and A. Stroombergen, 2021: Impacts and implications of climate change on wastewater systems: A New Zealand perspective. *Climate Risk Management*, **31**, 100262. https://doi.org/10.1016/j.crm.2020.100262

75. Kirchhoff, C.J. and P.L. Watson, 2019: Are wastewater systems adapting to climate change? JAWRA *Journal of the American Water Resources Association*, **55** (4), 869–880. https://doi.org/10.1111/1752-1688.12748

76. Sadler, J.M., J.L. Goodall, M. Behl, B.D. Bowes, and M.M. Morsy, 2020: Exploring real-time control of stormwater systems for mitigating flood risk due to sea level rise. *Journal of Hydrology*, **583**, 124571. https://doi.org/10.1016/j.jhydrol.2020.124571

77. Davtalab, R., A. Mirchi, R.J. Harris, M.X. Troilo, and K. Madani, 2020: Sea level rise effect on groundwater rise and stormwater retention pond reliability. *Water*, **12** (4), 1129. https://doi.org/10.3390/w12041129

78. Fant, C., J.M. Jacobs, P. Chinowsky, W. Sweet, N. Weiss, J.E. Sias, J. Martinich, and J.E. Neumann, 2021: Mere nuisance or growing threat? The physical and economic impact of high tide flooding on US road networks. *Journal of Infrastructure Systems*, **27** (4), 04021044. https://doi.org/10.1061/(asce)is.1943-555x.0000652

79. Hino, M., S.T. Belanger, C.B. Field, A.R. Davies, and K.J. Mach, 2019: High-tide flooding disrupts local economic activity. *Science Advances*, **5** (2), 2736. https://doi.org/10.1126/sciadv.aau2736

80. Hino, M. and M. Burke, 2021: The effect of information about climate risk on property values. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (17), e2003374118. https://doi.org/10.1073/pnas.2003374118

81. Jacobs, J.M., L.R. Cattaneo, W. Sweet, and T. Mansfield, 2018: Recent and future outlooks for nuisance flooding impacts on roadways on the U.S. East Coast. *Transportation Research Record*, **2672** (2), 1–10. https://doi.org/10.1177/0361198118756366

82. Moser, S.C. and J.A.F. Hart, 2015: The long arm of climate change: Societal teleconnections and the future of climate change impacts studies. *Climatic Change*, **129** (1), 13–26. https://doi.org/10.1007/s10584-015-1328-z

83. Gibson, N., S. McNulty, C. Miller, M. Gavazzi, E. Worley, D. Keesee, and D. Hollinger, 2021: Identification, Mitigation, and Adaptation to Salinization on Working Lands in the U.S. Southeast. Gen. Tech. Rep. SRS-259. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 69 pp. https://doi.org/10.2737/srs-gtr-259

84. USDA, 2020: Saltwater Intrusion: A Growing Threat to Coastal Agriculture. U.S. Department of Agriculture, Northeast Climate Hub, 2 pp. https://www.climatehubs.usda.gov/hubs/northeast/topic/saltwater-intrusion-growing-threat-coastal-agriculture

85. Bick, I.A., A.F. Santiago Tate, K.A. Serafin, A. Miltenberger, I. Anyansi, M. Evans, L. Ortolano, D. Ouyang, and J. Suckale, 2021: Rising seas, rising inequity? Communities at risk in the San Francisco Bay Area and implications for adaptation policy. *Earth's Future*, **9** (7), e2020EF001963. https://doi.org/10.1029/2020ef001963

86. Handwerger, L.R., M.M. Sugg, and J.D. Runkle, 2021: Present and future sea level rise at the intersection of race and poverty in the Carolinas: A geospatial analysis. *The Journal of Climate Change and Health*, **3**, 100028. https://doi.org/10.1016/j.joclim.2021.100028

87. Tate, E., M.A. Rahman, C.T. Emrich, and C.C. Sampson, 2021: Flood exposure and social vulnerability in the United States. *Natural Hazards*, **106** (1), 435–457. https://doi.org/10.1007/s11069-020-04470-2

88. Berberian, A.G., D.J.X. Gonzalez, and L.J. Cushing, 2022: Racial disparities in climate change-related health effects in the United States. *Current Environmental Health Reports*, **9** (3), 451–464. https://doi.org/10.1007/s40572-022-00360-w

89. Lieberman-Cribbin, W., C. Gillezeau, R.M. Schwartz, and E. Taioli, 2021: Unequal social vulnerability to Hurricane Sandy flood exposure. *Journal of Exposure Science & Environmental Epidemiology*, **31** (5), 804–809. https://doi.org/10.1038/s41370-020-0230-6

90. Rhubart, D. and Y. Sun, 2021: The social correlates of flood risk: Variation along the US rural–urban continuum. *Population and Environment*, **43** (2), 232–256. https://doi.org/10.1007/s11111-021-00388-4

91. Flores, A.B., A. Castor, S.E. Grineski, T.W. Collins, and C. Mullen, 2021: Petrochemical releases disproportionately affected socially vulnerable populations along the Texas Gulf Coast after Hurricane Harvey. *Population and Environment*, **42** (3), 279–301. https://doi.org/10.1007/s11111-020-00362-6

92. Linscott, G., A. Rishworth, B. King, and M.P. Hiestand, 2022: Uneven experiences of urban flooding: Examining the 2010 Nashville flood. *Natural Hazards*, **110** (1), 629–653. https://doi.org/10.1007/s11069-021-04961-w

93. Nowak, D.J., A. Ellis, and E.J. Greenfield, 2022: The disparity in tree cover and ecosystem service values among redlining classes in the United States. *Landscape and Urban Planning*, **221**, 104370. https://doi.org/10.1016/j.landurbplan.2022.104370

94. An, B., A.W. Orlando, and S. Rodnyansky, 2019: The Physical Legacy of Racism: How Redlining Cemented the Modern Built Environment. Social Science Research Network. https://doi.org/10.2139/ssrn.3500612

95. Hui Mālama Loko Iʻa, 2020: Loko Iʻa Needs Assessment. University of Hawaiʻi, Sea Grant College Program and Pacific Islands Climate Adaptation Science Center. https://seagrant.soest.hawaii.edu/loko-i%CA%BBa-needs-assessment/

96. Tran, J., L.M. Divine, and L.R. Heffner, 2021: "What are you going to do, protest the wind?": Community perceptions of emergent and worsening coastal erosion from the remote Bering Sea community of St. Paul, Alaska. *Environmental Management*, **67** (1), 43–66. https://doi.org/10.1007/s00267-020-01382-6

97. Hampton, S. and J. Curtis, 2022: A bridge over troubled water? Flood insurance and the governance of climate change adaptation. *Geoforum*, **136**, 80–91. https://doi.org/10.1016/j.geoforum.2022.08.008

98. Netusil, N.R., C. Kousky, S. Neupane, W. Daniel, and H. Kunreuther, 2021: The willingness to pay for flood insurance. *Land Economics*, **97** (1), 17–38. https://doi.org/10.3368/wple.97.1.110819-0160r1

99. Best, K. and Z. Jouzi, 2022: Climate gentrification: Methods, gaps, and framework for future research. *Frontiers in Climate*, **4**, 828067. https://doi.org/10.3389/fclim.2022.828067

100. Hu, S., 2020: What is Climate Gentrification? Natural Resources Defense Council. https://www.nrdc.org/stories/what-climate-gentrification

101. Nguyen, A., 2021: What Is Climate Gentrification? Sustainable and Social. https://sustainableandsocial.com/climate-gentrification/

102. Gould, K.A. and T.L. Lewis, 2021: Resilience gentrification: Environmental privilege in an age of coastal climate disasters. *Frontiers in Sustainable Cities*, **3**, 687670. https://doi.org/10.3389/frsc.2021.687670

103. Javeline, D., T. Kijewski-Correa, and A. Chesler, 2019: Does it matter if you "believe" in climate change? Not for coastal home vulnerability. *Climatic Change*, **155** (4), 511–532. https://doi.org/10.1007/s10584-019-02513-7

104. Melix, B.L., A. Jackson, W. Butler, T. Holmes, and C.K. Uejio, 2022: Locating neighborhood displacement risks to climate gentrification pressures in three coastal counties in Florida. *The Professional Geographer*, **75** (1), 31–43. https://doi.org/10.1080/00330124.2022.2087695

105. Gittman, R.K., F.J. Fodrie, A.M. Popowich, D.A. Keller, J.F. Bruno, C.A. Currin, C.H. Peterson, and M.F. Piehler, 2015: Engineering away our natural defenses: An analysis of shoreline hardening in the US. *Frontiers in Ecology and the Environment*, **13** (6), 301–307. https://doi.org/10.1890/150065

106. Griggs, G. and K. Patsch, 2019: The protection/hardening of California's coast: Times are changing. *Journal of Coastal Research*, **35** (5), 1051–1061. https://doi.org/10.2112/jcoastres-d-19a-00007.1

107. Pelletier, J.D., A. Brad Murray, J.L. Pierce, P.R. Bierman, D.D. Breshears, B.T. Crosby, M. Ellis, E. Foufoula-Georgiou, A.M. Heimsath, C. Houser, N. Lancaster, M. Marani, D.J. Merritts, L.J. Moore, J.L. Pederson, M.J. Poulos, T.M. Rittenour, J.C. Rowland, P. Ruggiero, D.J. Ward, A.D. Wickert, and E.M. Yager, 2015: Forecasting the response of Earth's surface to future climatic and land use changes: A review of methods and research needs. *Earth's Future*, **3** (7), 220–251. https://doi.org/10.1002/2014ef000290

108. Bender, S.R., 2019: Ch. 7. Floodplain infrastructure and the toxic tide. In: *Impact of Water Pollution on Human Health and Environmental Sustainability*. McKeown, A.E. and G. Bugyi, Eds. IGI Global, 150–173. https://doi.org/10.4018/978-1-4666-9559-7.ch007

109. Colloff, M.J., R. Gorddard, N. Abel, B. Locatelli, C. Wyborn, J.R.A. Butler, S. Lavorel, L. van Kerkhoff, S. Meharg, C. Múnera-Roldán, E. Bruley, G. Fedele, R.M. Wise, and M. Dunlop, 2021: Adapting transformation and transforming adaptation to climate change using a pathways approach. *Environmental Science & Policy*, **124**, 163–174. https://doi.org/10.1016/j.envsci.2021.06.014

110. Barnard, P.L., J.E. Dugan, H.M. Page, N.J. Wood, J.A.F. Hart, D.R. Cayan, L.H. Erikson, D.M. Hubbard, M.R. Myers, J.M. Melack, and S.F. Iacobellis, 2021: Multiple climate change-driven tipping points for coastal systems. *Scientific Reports*, **11** (1), 15560. https://doi.org/10.1038/s41598-021-94942-7

111. Borchert, S.M., M.J. Osland, N.M. Enwright, and K.T. Griffith, 2018: Coastal wetland adaptation to sea level rise: Quantifying potential for landward migration and coastal squeeze. *Journal of Applied Ecology*, **55** (6), 2876–2887. https://doi.org/10.1111/1365-2664.13169

112. Ganju, N.K., B.R. Couvillion, Z. Defne, and K.V. Ackerman, 2022: Development and application of Landsat-based wetland vegetation cover and unvegetated-vegetated marsh ratio (UVVR) for the conterminous United States. *Estuaries and Coasts*, **45**, 1861–1878. https://doi.org/10.1007/s12237-022-01081-x

113. Tavares, K.-D., C.H. Fletcher, and T.R. Anderson, 2020: Risk of shoreline hardening and associated beach loss peaks before mid-century: O'ahu, Hawai'i. *Scientific Reports*, **10** (1), 13633. https://doi.org/10.1038/s41598-020-70577-y

114. Menéndez, P., I.J. Losada, S. Torres-Ortega, S. Narayan, and M.W. Beck, 2020: The global flood protection benefits of mangroves. *Scientific Reports*, **10** (1), 4404. https://doi.org/10.1038/s41598-020-61136-6

115. Temmerman, S., E.M. Horstman, K.W. Krauss, J.C. Mullarney, I. Pelckmans, and K. Schoutens, 2023: Marshes and mangroves as nature-based coastal storm buffers. *Annual Review of Marine Science*, **15**, 95–118. https://doi.org/10.1146/annurev-marine-040422-092951

116. Campbell, A.D., L. Fatoyinbo, L. Goldberg, and D. Lagomasino, 2022: Global hotspots of salt marsh change and carbon emissions. *Nature*, **612** (7941), 701–706. https://doi.org/10.1038/s41586-022-05355-z

117. Weis, J.S., E.B. Watson, B. Ravit, C. Harman, and M. Yepsen, 2021: The status and future of tidal marshes in New Jersey faced with sea level rise. *Anthropocene Coasts*, **4** (1), 168–192. https://doi.org/10.1139/anc-2020-0020

118. Fagherazzi, S., G. Mariotti, N. Leonardi, A. Canestrelli, W. Nardin, and W.S. Kearney, 2020: Salt marsh dynamics in a period of accelerated sea level rise. *Journal of Geophysical Research: Earth Surface*, **125** (8), e2019JF005200. https://doi.org/10.1029/2019jf005200

119. Osland, M.J., B. Chivoiu, N.M. Enwright, K.M. Thorne, G.R. Guntenspergen, J.B. Grace, L.L. Dale, W. Brooks, N. Herold, J.W. Day, F.H. Sklar, and C.M. Swarzenzki, 2022: Migration and transformation of coastal wetlands in response to rising seas. *Science Advances*, **8** (26), 5174. https://doi.org/10.1126/sciadv.abo5174

120. Buchanan, M.K., S. Kulp, and B. Strauss, 2022: Resilience of U.S. coastal wetlands to accelerating sea level rise. *Environmental Research Communications*, **4** (6), 061001. https://doi.org/10.1088/2515-7620/ac6eef

121. Schieder, N.W., D.C. Walters, and M.L. Kirwan, 2018: Massive upland to wetland conversion compensated for historical marsh loss in Chesapeake Bay, USA. *Estuaries and Coasts*, **41** (4), 940–951. https://doi.org/10.1007/s12237-017-0336-9

122. Raabe, E.A. and R.P. Stumpf, 2016: Expansion of tidal marsh in response to sea-level rise: Gulf Coast of Florida, USA. *Estuaries and Coasts*, **39** (1), 145–157. https://doi.org/10.1007/s12237-015-9974-y

123. Armitage, A.R., W.E. Highfield, S.D. Brody, and P. Louchouarn, 2015: The contribution of mangrove expansion to salt marsh loss on the Texas Gulf Coast. *PLoS ONE*, **10** (5), 0125404. https://doi.org/10.1371/journal.pone.0125404

124. Thorne, K., G. MacDonald, G. Guntenspergen, R. Ambrose, K. Buffington, B. Dugger, C. Freeman, C. Janousek, L. Brown, J. Rosencranz, J. Holmquist, J. Smol, K. Hargan, and J. Takekawa, 2018: U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise. *Science Advances*, **4** (2), eaao3270. https://doi.org/10.1126/sciadv.aao3270

125. Barbier, E.B., S.D. Hacker, C. Kennedy, E.W. Koch, A.C. Stier, and B.R. Silliman, 2011: The value of estuarine and coastal ecosystem services. *Ecological Monographs*, **81** (2), 169–193. https://doi.org/10.1890/10-1510.1

126. Correll, M.D., W.A. Wiest, B.J. Olsen, W.G. Shriver, C.S. Elphick, and T.P. Hodgman, 2016: Habitat specialization explains avian persistence in tidal marshes. *Ecosphere*, **7** (11), e01506. https://doi.org/10.1002/ecs2.1506

127. Narayan, S., M.W. Beck, P. Wilson, C.J. Thomas, A. Guerrero, C.C. Shepard, B.G. Reguero, G. Franco, J.C. Ingram, and D. Trespalacios, 2017: The value of coastal wetlands for flood damage reduction in the northeastern USA. *Scientific Reports*, **7** (1), 9463. https://doi.org/10.1038/s41598-017-09269-z

128. Shepard, C.C., C.M. Crain, and M.W. Beck, 2011: The protective role of coastal marshes: A systematic review and meta-analysis. *PLoS ONE*, **6** (11), e27374. https://doi.org/10.1371/journal.pone.0027374

129. Spalding, M.D., S. Ruffo, C. Lacambra, I. Meliane, L.Z. Hale, C.C. Shepard, and M.W. Beck, 2014: The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean & Coastal Management*, **90**, 50–57. https://doi.org/10.1016/j.ocecoaman.2013.09.007

130. Lorenzo-Trueba, J. and A.D. Ashton, 2014: Rollover, drowning, and discontinuous retreat: Distinct modes of barrier response to sea-level rise arising from a simple morphodynamic model. *Journal of Geophysical Research: Earth Surface*, **119** (4), 779–801. https://doi.org/10.1002/2013jf002941

131. Miselis, J.L. and J. Lorenzo-Trueba, 2017: Natural and human-induced variability in barrier-island response to sea level rise. *Geophysical Research Letters*, **44** (23), 11922–11931. https://doi.org/10.1002/2017gl074811

132. Passeri, D.L., P.S. Dalyander, J.W. Long, R.C. Mickey, R.L. Jenkins III, D.M. Thompson, N.G. Plant, E.S. Godsey, and V.M. Gonzalez, 2020: The roles of storminess and sea level rise in decadal barrier island evolution. *Geophysical Research Letters*, **47** (18), e2020GL089370. https://doi.org/10.1029/2020gl089370

133. Reeves, I.R.B., L.J. Moore, E.B. Goldstein, A.B. Murray, J.A. Carr, and M.L. Kirwan, 2020: Impacts of seagrass dynamics on the coupled long-term evolution of barrier-marsh-bay systems. *Journal of Geophysical Research: Biogeosciences*, **125** (2), e2019JG005416. https://doi.org/10.1029/2019jg005416

134. Rogers, L.J., L.J. Moore, E.B. Goldstein, C.J. Hein, J. Lorenzo-Trueba, and A.D. Ashton, 2015: Anthropogenic controls on overwash deposition: Evidence and consequences. *Journal of Geophysical Research Earth Surface*, **120** (12), 2609–2624. https://doi.org/10.1002/2015jf003634

135. Zinnert, J.C., S.M. Via, B.P. Nettleton, P.A. Tuley, L.J. Moore, and J.A. Stallins, 2019: Connectivity in coastal systems: Barrier island vegetation influences upland migration in a changing climate. *Global Change Biology*, **25** (7), 2419–2430. https://doi.org/10.1111/gcb.14635

136. Dow, K., F. Berkhout, B.L. Preston, R.J.T. Klein, G. Midgley, and M.R. Shaw, 2013: Limits to adaptation. *Nature Climate Change*, **3** (4), 305–307. https://doi.org/10.1038/nclimate1847

137. Ward, N.D., J.P. Megonigal, B. Bond-Lamberty, V.L. Bailey, D. Butman, E.A. Canuel, H. Diefenderfer, N.K. Ganju, M.A. Goñi, E.B. Graham, C.S. Hopkinson, T. Khangaonkar, J.A. Langley, N.G. McDowell, A.N. Myers-Pigg, R.B. Neumann, C.L. Osburn, R.M. Price, J. Rowland, A. Sengupta, M. Simard, P.E. Thornton, M. Tzortziou, R. Vargas, P.B. Weisenhorn, and L. Windham-Myers, 2020: Representing the function and sensitivity of coastal interfaces in Earth system models. *Nature Communications*, **11** (1), 2458. https://doi.org/10.1038/s41467-020-16236-2

138. Enwright, N.M., K.T. Griffith, and M.J. Osland, 2016: Barriers to and opportunities for landward migration of coastal wetlands with sea-level rise. *Frontiers in Ecology and the Environment*, **14** (6), 307–316. https://doi.org/10.1002/fee.1282

139. Gedan, K.B. and E. Fernández-Pascual, 2019: Salt marsh migration into salinized agricultural fields: A novel assembly of plant communities. *Journal of Vegetation Science*, **30** (5), 1007–1016. https://doi.org/10.1111/jvs.12774

140. Davis, R.A., 2019: Human impact on coasts. In: *Encyclopedia of Coastal Science*. Finkl, C.W. and C. Makowski, Eds. Springer, Cham, Switzerland, 983–991. https://doi.org/10.1007/978-3-319-93806-6_175

141. Rasmussen, D.J., M.K. Buchanan, R.E. Kopp, and M. Oppenheimer, 2020: A flood damage allowance framework for coastal protection with deep uncertainty in sea level rise. *Earth's Future*, **8** (3), e2019EF001340. https://doi.org/10.1029/2019ef001340

142. Fuentes, M., 2020: Rising sea levels will become California's greatest land use challenge: How the state of California must take a stronger role in requiring local governments to adopt adaptive land use controls in order to prevent economic and environmental destruction resulting from sea level rise. *Environs: Environmental Law and Policy Journal*, **44** (1). https://environs.law.ucdavis.edu/volumes/44/1/fuentes.pdf

143. Zhao, L. and F. Liu, 2020: Land-use planning adaptation in response to SLR based on a vulnerability analysis. *Ocean & Coastal Management*, **196**, 105297. https://doi.org/10.1016/j.ocecoaman.2020.105297

144. Guerry, A.D., J. Silver, J. Beagle, K. Wyatt, K. Arkema, J. Lowe, P. Hamel, R. Griffin, S. Wolny, E. Plane, M. Griswold, H. Papendick, and J. Sharma, 2022: Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise. *npj Urban Sustainability*, **2** (1), 13. https://doi.org/10.1038/s42949-022-00056-y

145. Butler, W.H., R.E. Deyle, and C. Mutnansky, 2016: Low-regrets incrementalism: Land use planning adaptation to accelerating sea level rise in Florida's coastal communities. *Journal of Planning Education and Research*, **36** (3), 319–332. https://doi.org/10.1177/0739456x16647161

146. Burgos, A.G., B.D. Hamlington, P.R. Thompson, and R.D. Ray, 2018: Future nuisance flooding in Norfolk, VA, from astronomical tides and annual to decadal internal climate variability. *Geophysical Research Letters*, **45** (22), 12432–12439. https://doi.org/10.1029/2018gl079572

147. Norfolk City Council, 2022: The General Plan of the City of Norfolk. City of Norfolk, Norfolk, VA. https://www.norfolk.gov/DocumentCenter/View/2483/plaNorfolk2030?bidId

148. Waggonner & Ball, n.d.: Norfolk Ohio Creek Watershed Resilience. Waggonner & Ball Architecture/Environment, New Orleans, LA, accessed September 19, 2022. https://wbae.com/projects/norfolk-ohio-creek-watershed-resilience/

149. Bridges, T.S., J.K. King, J.D. Simm, M.W. Beck, G. Collins, Q. Lodder, and R.K. Mohan, 2021: International Guidelines on Natural and Nature-Based Features for Flood Risk Management. Special Report No. ERDC SR-21-6. U.S. Engineer Research and Development Center, Vicksburg, MS. https://doi.org/10.21079/11681/41946

150. Ommer, J., E. Bucchignani, L.S. Leo, M. Kalas, S. Vranić, S. Debele, P. Kumar, H.L. Cloke, and S. Di Sabatino, 2022: Quantifying co-benefits and disbenefits of nature-based solutions targeting disaster risk reduction. *International Journal of Disaster Risk Reduction*, **75**, 102966. https://doi.org/10.1016/j.ijdrr.2022.102966

151. Veerkamp, C., E. Ramieri, L. Romanovska, M. Zandersen, J. Förster, M. Rogger, and L. Martinsen, 2021: Assessment Frameworks of Nature-based Solutions for Climate Change Adaptation and Disaster Risk Reduction. ETC/CCA Technical Paper - 2021/3. European Topic Centre Climate Change Impacts, Vulnerability and Adaptation. https://doi.org/10.25424/cmcc/nbs_assessment_approaches

152. Vouk, I., V. Pilechi, M. Provan, and E. Murphy, 2021: Nature-Based Solutions for Coastal and Riverine Flood and Erosion Risk Management. Canadian Standards Association, Toronto, ON. https://www.csagroup.org/article/research/nature-based-solutions-for-coastal-and-riverine-flood-and-erosion-risk-management/

153. Bridges, T.S., P.W. Wagner, K.A. Burks-Copes, M.E. Bates, Z.A. Collier, J.C. Fischenich, J.Z. Gailani, L.D. Leuck, C.D. Piercy, J.D. Rosati, E.J. Russo, D.J. Shafer, B.C. Suedel, E.A. Vuxton, and T.V. Wamsley, 2015: Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience. ERDC SR-15-1. U.S. Army Corps of Engineers, Engineer Research and Development Center, Environmental Laboratory. https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/3442/

154. Garzon, J.L., M. Maza, C.M. Ferreira, J.L. Lara, and I.J. Losada, 2019: Wave attenuation by Spartina saltmarshes in the Chesapeake Bay under storm surge conditions. *Journal of Geophysical Research: Oceans*, **124** (7), 5220–5243. https://doi.org/10.1029/2018jc014865

155. Maza, M., J.L. Lara, and I.J. Losada, 2021: Predicting the evolution of coastal protection service with mangrove forest age. *Coastal Engineering*, **168**, 103922. https://doi.org/10.1016/j.coastaleng.2021.103922

156. Möller, I., M. Kudella, F. Rupprecht, T. Spencer, M. Paul, B.K. van Wesenbeeck, G. Wolters, K. Jensen, T.J. Bouma, M. Miranda-Lange, and S. Schimmels, 2014: Wave attenuation over coastal salt marshes under storm surge conditions. *Nature Geoscience*, **7** (10), 727–731. https://doi.org/10.1038/ngeo2251

157. Pennings, S.C., R.M. Glazner, Z.J. Hughes, J.S. Kominoski, and A.R. Armitage, 2021: Effects of mangrove cover on coastal erosion during a hurricane in Texas, USA. *Ecology*, **102** (4), e03309. https://doi.org/10.1002/ecy.3309

158. Fairchild, T.P., W.G. Bennett, G. Smith, B. Day, M.W. Skov, I. Möller, N. Beaumont, H. Karunarathna, and J.N. Griffin, 2021: Coastal wetlands mitigate storm flooding and associated costs in estuaries. *Environmental Research Letters*, **16** (7), 074034. https://doi.org/10.1088/1748-9326/ac0c45

159. Glass, E.M., J.L. Garzon, S. Lawler, E. Paquier, and C.M. Ferreira, 2018: Potential of marshes to attenuate storm surge water level in the Chesapeake Bay. *Limnology and Oceanography*, **63** (2), 951–967. https://doi.org/10.1002/lno.10682

160. Figlus, J., 2022: Ch. 21. Designing and implementing coastal dunes for flood risk reduction. In: *Coastal Flood Risk Reduction*. Brody, S., Y. Lee, and B.B. Kothuis, Eds. Elsevier, 287–301. https://doi.org/10.1016/b978-0-323-85251-7.00021-4

161. Beck, M.W., I.J. Losada, P. Menéndez, B.G. Reguero, P. Díaz-Simal, and F. Fernández, 2018: The global flood protection savings provided by coral reefs. *Nature Communications*, **9** (1), 2186. https://doi.org/10.1038/s41467-018-04568-z

162. Reguero, B.G., C.D. Storlazzi, A.E. Gibbs, J.B. Shope, A.D. Cole, K.A. Cumming, and M.W. Beck, 2021: The value of US coral reefs for flood risk reduction. *Nature Sustainability*, **4** (8), 688–698. https://doi.org/10.1038/s41893-021-00706-6

163. Storlazzi, C.D., B.G. Reguero, A.D. Cole, E. Lowe, J.B. Shope, A.E. Gibbs, B.A. Nickel, R.T. McCall, A.R. van Dongeren, and M.W. Beck, 2019: Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction. USGS Open-File Report 2019–1027. U.S. Geological Survey, Reston, VA, 42 pp. https://doi.org/10.3133/ofr20191027

164. Bilkovic, D.M., M.M. Mitchell, M.K. La Peyre, and J.D.E. Toft, Eds., 2017: *Living Shorelines: The Science and Management of Nature-Based Coastal Protection*. 1st ed., CRC Press, Boca Raton, FL, 519 pp. https://doi.org/10.1201/9781315151465

165. Morris, R.L., M.K. La Peyre, B.M. Webb, D.A. Marshall, D.M. Bilkovic, J. Cebrian, G. McClenachan, K.M. Kibler, L.J. Walters, D. Bushek, E.L. Sparks, N.A. Temple, J. Moody, K. Angstadt, J. Goff, M. Boswell, P. Sacks, and S.E. Swearer, 2021: Large-scale variation in wave attenuation of oyster reef living shorelines and the influence of inundation duration. *Ecological Applications*, **31** (6), e02382. https://doi.org/10.1002/eap.2382

166. Marin-Diaz, B., G.S. Fivash, J. Nauta, R.J.M. Temmink, N. Hijner, V.C. Reijers, P.P.M.J.M. Cruijsen, K. Didderen, J.H.T. Heusinkveld, E. Penning, G. Maldonado-Garcia, J. van Belzen, J.C. de Smit, M.J.A. Christianen, T. van der Heide, D. van der Wal, H. Olff, T.J. Bouma, and L.L. Govers, 2021: On the use of large-scale biodegradable artificial reefs for intertidal foreshore stabilization. *Ecological Engineering*, **170**, 106354. https://doi.org/10.1016/j.ecoleng.2021.106354

167. FEMA, 2021: Building Community Resilience with Nature-Based Solutions: A Guide for Local Communities. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_riskmap-nature-based-solutions-guide_2021.pdf

168. Green-Gray Community of Practice, 2020: Practical Guide to Implementing Green-Gray Infrastructure. Green-Gray Community of Practice. https://www.conservation.org/projects/global-green-gray-community-of-practice

169. Webb, B., B. Dix, S. Douglass, S. Asam, C. Cherry, and B. Buhring, 2019: Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide. FHWA-HEP-19-042. U.S. Department of Transportation, Federal Highway Administration, Washington DC. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/implementation_guide/

170. Mitchell, M. and D.M. Bilkovic, 2019: Embracing dynamic design for climate-resilient living shorelines. *Journal of Applied Ecology*, **56** (5), 1099–1105. https://doi.org/10.1111/1365-2664.13371

171. Nunez, K., T. Rudnicky, P. Mason, C. Tombleson, and M. Berman, 2022: A geospatial modeling approach to assess site suitability of living shorelines and emphasize best shoreline management practices. *Ecological Engineering*, **179**, 106617. https://doi.org/10.1016/j.ecoleng.2022.106617

172. Ajibade, I., M. Sullivan, and M. Haeffner, 2020: Why climate migration is not managed retreat: Six justifications. *Global Environmental Change*, **65**, 102187. https://doi.org/10.1016/j.gloenvcha.2020.102187

173. Fussell, E. and B. Castro, 2022: Ch. 10. Environmentally informed migration in North America. In: *International Handbook of Population and Environment*. Hunter, L.M., C. Gray, and J. Véron, Eds. Springer, Cham, Switzerland, 205–223. https://doi.org/10.1007/978-3-030-76433-3_10

174. Bragg, W.K., S.T. Gonzalez, A. Rabearisoa, and A.D. Stoltz, 2021: Communicating managed retreat in California. *Water*, **13** (6), 781. https://doi.org/10.3390/w13060781

175. McGhee, D.J., S.B. Binder, and E.A. Albright, 2020: First, do no harm: Evaluating the vulnerability reduction of post-disaster home buyout programs. *Natural Hazards Review*, **21** (1), 05019002. https://doi.org/10.1061/(asce)nh.1527-6996.0000337

176. Simms, J.R.Z., H.L. Waller, C. Brunet, and P. Jenkins, 2021: The long goodbye on a disappearing, ancestral island: A just retreat from Isle de Jean Charles. *Journal of Environmental Studies and Sciences*, **11**, 316–328. https://doi.org/10.1007/s13412-021-00682-5

177. Palinkas, L.A., 2020: Ch. 7. Fleeing coastal erosion: Kivalina and Isle de Jean Charles. In: *Global Climate Change, Population Displacement, and Public Health*. Springer, Cham, Switzerland, 127–145. https://doi.org/10.1007/978-3-030-41890-8_7

178. Ajibade, I., M. Sullivan, C. Lower, L. Yarina, and A. Reilly, 2022: Are managed retreat programs successful and just? A global mapping of success typologies, justice dimensions, and trade-offs. *Global Environmental Change*, **76**, 102576. https://doi.org/10.1016/j.gloenvcha.2022.102576

179. Siders, A.R., 2019: Managed retreat in the United States. *One Earth*, **1** (2), 216–225. https://doi.org/10.1016/j.oneear.2019.09.008

180. Griggs, G. and B.G. Reguero, 2021: Coastal adaptation to climate change and sea-level rise. *Water*, **13** (16), 2151. https://doi.org/10.3390/w13162151

181. Priestley, R.K., Z. Heine, and T.L. Milfont, 2021: Public understanding of climate change-related sea-level rise. *PLoS ONE*, **16** (7), e0254348. https://doi.org/10.1371/journal.pone.0254348

182. Noy, I., 2020: Paying a price of climate change: Who pays for managed retreats? *Current Climate Change Reports*, **6** (1), 17–23. https://doi.org/10.1007/s40641-020-00155-x

183. Hino, M., C.B. Field, and K.J. Mach, 2017: Managed retreat as a response to natural hazard risk. *Nature Climate Change*, **7** (5), 364–370. https://doi.org/10.1038/nclimate3252

184. Tubridy, F., M. Lennon, and M. Scott, 2022: Managed retreat and coastal climate change adaptation: The environmental justice implications and value of a coproduction approach. *Land Use Policy*, **114**, 105960. https://doi.org/10.1016/j.landusepol.2021.105960

185. O'Donnell, T., 2022: Managed retreat and planned retreat: A systematic literature review. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **377** (1854), 20210129. https://doi.org/10.1098/rstb.2021.0129

186. Fitton, J.M., K.A. Addo, P.-N. Jayson-Quashigah, G.J. Nagy, O. Gutiérrez, D. Panario, I. Carro, L. Seijo, C. Segura, J.E. Verocai, S. Luoma, J. Klein, T.-T. Zhang, J. Birchall, and P. Stempel, 2021: Challenges to climate change adaptation in coastal small towns: Examples from Ghana, Uruguay, Finland, Denmark, and Alaska. *Ocean & Coastal Management*, **212**, 105787. https://doi.org/10.1016/j.ocecoaman.2021.105787

187. Howell, J. and J.R. Elliott, 2018: As disaster costs rise, so does inequality. *Socius*, **4**, 2378023118816795. https://doi.org/10.1177/2378023118816795

188. Fleming, E., J. Payne, W. Sweet, M. Craghan, J. Haines, J.F. Hart, H. Stiller, and A. Sutton-Grier, 2018: Ch. 8. Coastal effects. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 322–352. https://doi.org/10.7930/nca4.2018.ch8

189. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

190. Dangendorf, S., C. Hay, F.M. Calafat, M. Marcos, C.G. Piecuch, K. Berk, and J. Jensen, 2019: Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change*, **9** (9), 705–710. https://doi.org/10.1038/s41558-019-0531-8

191. Frederikse, T., F. Landerer, L. Caron, S. Adhikari, D. Parkes, V.W. Humphrey, S. Dangendorf, P. Hogarth, L. Zanna, L. Cheng, and Y.-H. Wu, 2020: The causes of sea-level rise since 1900. *Nature*, **584** (7821), 393–397. https://doi.org/10.1038/s41586-020-2591-3

192. Hamlington, B.D., M. Osler, N. Vinogradova, and W.V. Sweet, 2021: Coordinated science support for sea-level data and services in the United States. *AGU Advances*, **2** (2), e2021AV000418. https://doi.org/10.1029/2021av000418

193. Edwards, T.L., S. Nowicki, B. Marzeion, R. Hock, H. Goelzer, H. Seroussi, N.C. Jourdain, D.A. Slater, F.E. Turner, C.J. Smith, C.M. McKenna, E. Simon, A. Abe-Ouchi, J.M. Gregory, E. Larour, W.H. Lipscomb, A.J. Payne, A. Shepherd, C. Agosta, P. Alexander, T. Albrecht, B. Anderson, X. Asay-Davis, A. Aschwanden, A. Barthel, A. Bliss, R. Calov, C. Chambers, N. Champollion, Y. Choi, R. Cullather, J. Cuzzone, C. Dumas, D. Felikson, X. Fettweis, K. Fujita, B.K. Galton-Fenzi, R. Gladstone, N.R. Golledge, R. Greve, T. Hattermann, M.J. Hoffman, A. Humbert, M. Huss, P. Huybrechts, W. Immerzeel, T. Kleiner, P. Kraaijenbrink, S. Le clec'h, V. Lee, G.R. Leguy, C.M. Little, D.P. Lowry, J.-H. Malles, D.F. Martin, F. Maussion, M. Morlighem, J.F. O'Neill, I. Nias, F. Pattyn, T. Pelle, S.F. Price, A. Quiquet, V. Radić, R. Reese, D.R. Rounce, M. Rückamp, A. Sakai, C. Shafer, N.-J. Schlegel, S. Shannon, R.S. Smith, F. Straneo, S. Sun, L. Tarasov, L.D. Trusel, J. Van Breedam, R. van de Wal, M. van den Broeke, R. Winkelmann, H. Zekollari, C. Zhao, T. Zhang, and T. Zwinger, 2021: Projected land ice contributions to twenty-first-century sea level rise. *Nature*, **593** (7857), 74–82. https://doi.org/10.1038/s41586-021-03302-y

194. Taherkhani, M., S. Vitousek, P.L. Barnard, N. Frazer, T.R. Anderson, and C.H. Fletcher, 2020: Sea-level rise exponentially increases coastal flood frequency. *Scientific Reports*, **10** (1), 6466. https://doi.org/10.1038/s41598-020-62188-4

195. USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 470 pp. https://doi.org/10.7930/j0j964j6

196. Chen, X. and L.R. Leung, 2020: Response of landfalling atmospheric rivers on the U.S. West Coast to local sea surface temperature perturbations. *Geophysical Research Letters*, **47** (18), e2020GL089254. https://doi.org/10.1029/2020gl089254

197. Hagos, S.M., L.R. Leung, J.-H. Yoon, J. Lu, and Y. Gao, 2016: A projection of changes in landfalling atmospheric river frequency and extreme precipitation over western North America from the Large Ensemble CESM simulations. *Geophysical Research Letters*, **43** (3), 1357–1363. https://doi.org/10.1002/2015gl067392

198. Patricola, C.M., M.F. Wehner, E. Bercos-Hickey, F.V. Maciel, C. May, M. Mak, O. Yip, A.M. Roche, and S. Leal, 2022: Future changes in extreme precipitation over the San Francisco Bay Area: Dependence on atmospheric river and extratropical cyclone events. *Weather and Climate Extremes*, **36**, 100440. https://doi.org/10.1016/j.wace.2022.100440

199. Hauer, M.E., J.M. Evans, and D.R. Mishra, 2016: Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change*, **6** (7), 691–695. https://doi.org/10.1038/nclimate2961

200. Merkens, J.-L., L. Reimann, J. Hinkel, and A.T. Vafeidis, 2016: Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Global and Planetary Change*, **145**, 57–66. https://doi.org/10.1016/j.gloplacha.2016.08.009

201. Strauss, B.H., S.A. Kulp, D.J. Rasmussen, and A. Levermann, 2021: Unprecedented threats to cities from multi-century sea level rise. *Environmental Research Letters*, **16** (11), 114015. https://doi.org/10.1088/1748-9326/ac2e6b

202. Kirwan, M.L. and K.B. Gedan, 2019: Sea-level driven land conversion and the formation of ghost forests. *Nature Climate Change*, **9** (6), 450–457. https://doi.org/10.1038/s41558-019-0488-7

203. Kirwan, M.L., G.R. Guntenspergen, A. D'Alpaos, J.T. Morris, S.M. Mudd, and S. Temmerman, 2010: Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters*, **37** (23), L23401. https://doi.org/10.1029/2010gl045489

204. Siverd, C.G., S.C. Hagen, M.V. Bilskie, D.H. Braud, and R.R. Twilley, 2020: Quantifying storm surge and risk reduction costs: A case study for Lafitte, Louisiana. *Climatic Change*, **161** (1), 201–223. https://doi.org/10.1007/s10584-019-02636-x

205. Weiskopf, S.R., M.A. Rubenstein, L.G. Crozier, S. Gaichas, R. Griffis, J.E. Halofsky, K.J. Hyde, T.L. Morelli, J.T. Morisette, R.C. Muñoz, A.J. Pershing, D.L. Petersone, R. Poudel, M.D. Staudinger, A.E. Sutton-Grier, L. Thompson, J. Vose, J.F. Weltzin, and K.P. Whyte, 2020: Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, **733**, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782

206. Gittman, R.K., S.B. Scyphers, C.S. Smith, I.P. Neylan, and J.H. Grabowski, 2016: Ecological consequences of shoreline hardening: A meta-analysis. *BioScience*, **66**, 763–773. https://doi.org/10.1093/biosci/biw091

207. Bouwer, L.M., 2019: Ch. 3. Observed and projected impacts from extreme weather events: Implications for loss and damage. In: *Loss and Damage from Climate Change: Concepts, Methods and Policy Options*. Mechler, R., L.M. Bouwer, T. Schinko, S. Surminski, and J. Linnerooth-Bayer, Eds. Springer, Cham, Switzerland, 63–82. https://doi.org/10.1007/978-3-319-72026-5_3

208. Smiley, K.T., I. Noy, M.F. Wehner, D. Frame, C.C. Sampson, and O.E.J. Wing, 2022: Social inequalities in climate change-attributed impacts of Hurricane Harvey. *Nature Communications*, **13** (1), 3418. https://doi.org/10.1038/s41467-022-31056-2

209. Al-Attabi, Z., Y. Xu, G. Tso, and S. Narayan, 2023: The impacts of tidal wetland loss and coastal development on storm surge damages to people and property: A Hurricane Ike case-study. *Scientific Reports*, **13** (1), 4620. https://doi.org/10.1038/s41598-023-31409-x

210. Coutu, P., 2018: Tidal flooding could pose serious problems for Chesapeake Bay restoration, professor says. *The Virginian-Pilot*, November 2, 2018. https://www.pilotonline.com/news/environment/article_39835cd2-d798-11e8-87a8-9be3908f9d79.html

211. Makwana, N., 2019: Disaster and its impact on mental health: A narrative review. *Journal of Family Medicine and Primary Care*, **8** (10). https://doi.org/10.4103/jfmpc.jfmpc_893_19

212. Erickson, T.B., J. Brooks, E.J. Nilles, P.N. Pham, and P. Vinck, 2019: Environmental health effects attributed to toxic and infectious agents following hurricanes, cyclones, flash floods and major hydrometeorological events. *Journal of Toxicology and Environmental Health, Part B*, **22** (5–6), 157–171. https://doi.org/10.1080/10937404.2019.1654422

213. Gobler, C.J., 2020: Climate change and harmful algal blooms: Insights and perspective. *Harmful Algae*, **91**, 101731. https://doi.org/10.1016/j.hal.2019.101731

214. Raker, E.J., 2022: Climate-related disasters and children's health: Evidence from Hurricane Harvey. *Socius*, **8**, 23780231221135971. https://doi.org/10.1177/23780231221135971

215. Conzelmann, C., A. Salazar-Miranda, T. Phan, and J.S. Hoffman, 2022: Long-Term Causal Effects of Redlining on Environmental Risk Exposure. Working Paper 22-09R. Federal Reserve Bank of Richmond. https://doi.org/10.21144/wp22-09

216. Erman, A., E. Motte, R. Goyal, A. Asare, S. Takamatsu, X. Chen, S. Malgioglio, A. Skinner, N. Yoshida, and S. Hallegatte, 2020: The road to recovery the role of poverty in the exposure, vulnerability and resilience to floods in Accra. *Economics of Disasters and Climate Change*, **4** (1), 171–193. https://doi.org/10.1007/s41885-019-00056-w

217. Griego, A.L., A.B. Flores, T.W. Collins, and S.E. Grineski, 2020: Social vulnerability, disaster assistance, and recovery: A population-based study of Hurricane Harvey in Greater Houston, Texas. *International Journal of Disaster Risk Reduction*, **51**, 101766. https://doi.org/10.1016/j.ijdrr.2020.101766

218. Sou, G., D. Shaw, and F. Aponte-Gonzalez, 2021: A multidimensional framework for disaster recovery: Longitudinal qualitative evidence from Puerto Rican households. *World Development*, **144**, 105489. https://doi.org/10.1016/j.worlddev.2021.105489

219. Dundon, L.A. and J.S. Camp, 2021: Climate justice and home-buyout programs: Renters as a forgotten population in managed retreat actions. *Journal of Environmental Studies and Sciences*, **11**, 420–433. https://doi.org/10.1007/s13412-021-00691-4

220. Bento, A. and J.R. Elliott, 2022: The racially unequal impacts of disasters and federal recovery assistance on local self-employment rates. *Social Currents*, **9** (2), 118–138. https://doi.org/10.1177/23294965211028841

221. EcoSystems, 2014: Preparing for Sea Level Rise through Hazard Mitigation: Analysis of Risks & Recommendations. EcoSystems, Inc. https://coastalresilience.tamu.edu/files/2014/06/Sea-Level-Rise_Final.pdf

222. WSAV, 2018: Infrastructure upgrades for Tybee Island. *WSAV News*, September 18, 2018. https://www.wsav.com/news/local-news/infrastructure-upgrades-for-tybee-island/

223. Coutu, P., 2021: In Norfolk, sea level rise reduces some stormwater system capacity by 50%, data shows. *The Virginian-Pilot*, January 3, 2021. https://www.pilotonline.com/news/environment/vp-nw-fz20-sensor-stormwater-flooding-norfolk-20210103-t4jofv7hbff3dgcposbf7z7p5m-story.html

224. Fagherazzi, S., M.L. Kirwan, S.M. Mudd, G.R. Guntenspergen, S. Temmerman, A. D'Alpaos, J. van de Koppel, J.M. Rybczyk, E. Reyes, C. Craft, and J. Clough, 2012: Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors. *Reviews of Geophysics*, **50** (1). https://doi.org/10.1029/2011rg000359

225. Kirwan, M.L., S. Temmerman, E.E. Skeehan, G.R. Guntenspergen, and S. Fagherazzi, 2016: Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change*, **6** (3), 253–260. https://doi.org/10.1038/nclimate2909

226. Ganju, N.K., Z. Defne, M.L. Kirwan, S. Fagherazzi, A. D'Alpaos, and L. Carniello, 2017: Spatially integrative metrics reveal hidden vulnerability of microtidal salt marshes. *Nature Communications*, **8** (1), 14156. https://doi.org/10.1038/ncomms14156

227. Luijendijk, A., G. Hagenaars, R. Ranasinghe, F. Baart, G. Donchyts, and S. Aarninkhof, 2018: The state of the world's beaches. *Scientific Reports*, **8** (1), 6641. https://doi.org/10.1038/s41598-018-24630-6

228. Vitousek, S., K. Vos, K.D. Splinter, L. Erikson, and P.L. Barnard, 2023: A model integrating satellite-derived shoreline observations for predicting fine-scale shoreline response to waves and sea-level rise across large coastal regions. *Journal of Geophysical Research: Earth Surface*, **128** (7), e2022JF006936. https://doi.org/10.1029/2022JF006936

229. Vos, K., M.D. Harley, K.D. Splinter, J.A. Simmons, and I.L. Turner, 2019: Sub-annual to multi-decadal shoreline variability from publicly available satellite imagery. *Coastal Engineering*, **150**, 160–174. https://doi.org/10.1016/j.coastaleng.2019.04.004

230. Michael, H.A., V.E.A. Post, A.M. Wilson, and A.D. Werner, 2017: Science, society, and the coastal groundwater squeeze. *Water Resources Research*, **53** (4), 2610–2617. https://doi.org/10.1002/2017wr020851

231. Panthi, J., S.M. Pradhanang, A. Nolte, and T.B. Boving, 2022: Saltwater intrusion into coastal aquifers in the contiguous United States—A systematic review of investigation approaches and monitoring networks. *Science of The Total Environment*, **836**, 155641. https://doi.org/10.1016/j.scitotenv.2022.155641

232. Harden, C.P., A. Chin, M.R. English, R. Fu, K.A. Galvin, A.K. Gerlak, P.F. McDowell, D.E. McNamara, J.M. Peterson, N.L. Poff, E.A. Rosa, W.D. Solecki, and E.E. Wohl, 2014: Understanding human–landscape interactions in the "Anthropocene". *Environmental Management*, **53** (1), 4–13. https://doi.org/10.1007/s00267-013-0082-0

233. Lipiec, E., P. Ruggiero, A. Mills, K.A. Serafin, J. Bolte, P. Corcoran, J. Stevenson, C. Zanocco, and D. Lach, 2018: Mapping out climate change: Assessing how coastal communities adapt using alternative future scenarios. *Journal of Coastal Research*, **34** (5), 1196–1208. https://doi.org/10.2112/jcoastres-d-17-00115.1

234. Mullin, M., M.D. Smith, and D.E. McNamara, 2019: Paying to save the beach: Effects of local finance decisions on coastal management. *Climatic Change*, **152** (2), 275–289. https://doi.org/10.1007/s10584-018-2191-5

235. McNamara, D.E., A.B. Murray, and M.D. Smith, 2011: Coastal sustainability depends on how economic and coastline responses to climate change affect each other. *Geophysical Research Letters*, **38** (7). https://doi.org/10.1029/2011gl047207

236. Casey, A. and A. Becker, 2019: Institutional and conceptual barriers to climate change adaptation for coastal cultural heritage. *Coastal Management*, **47** (2), 169–188. https://doi.org/10.1080/08920753.2019.1564952

237. Singhvi, A., A.P. Luijendijk, and A.P.E. van Oudenhoven, 2022: The grey–green spectrum: A review of coastal protection interventions. *Journal of Environmental Management*, **311**, 114824. https://doi.org/10.1016/j.jenvman.2022.114824

238. Kelty, K., T. Tomiczek, D.T. Cox, P. Lomonaco, and W. Mitchell, 2022: Prototype-scale physical model of wave attenuation through a mangrove forest of moderate cross-shore thickness: Lidar-based characterization and Reynolds scaling for engineering with nature. *Frontiers in Marine Science*, **8**, 780946. https://doi.org/10.3389/fmars.2021.780946

239. Maza, M., J.L. Lara, and I.J. Losada, 2019: Experimental analysis of wave attenuation and drag forces in a realistic fringe *Rhizophora* mangrove forest. *Advances in Water Resources*, **131**, 103376. https://doi.org/10.1016/j.advwatres.2019.07.006

240. Smith, C.S., B. Puckett, R.K. Gittman, and C.H. Peterson, 2018: Living shorelines enhanced the resilience of saltmarshes to Hurricane Matthew (2016). *Ecological Applications*, **28** (4), 871–877. https://doi.org/10.1002/eap.1722

241. King, D., D. Bird, K. Haynes, H. Boon, A. Cottrell, J. Millar, T. Okada, P. Box, D. Keogh, and M. Thomas, 2014: Voluntary relocation as an adaptation strategy to extreme weather events. *International Journal of Disaster Risk Reduction*, **8**, 83–90. https://doi.org/10.1016/j.ijdrr.2014.02.006

242. Lester, C., G. Griggs, K. Patsch, and R. Anderson, 2022: Shoreline retreat in California: Taking a step back. *Journal of Coastal Research*, **38** (6), 1207–1230. https://doi.org/10.2112/jcoastres-d-22a-00010.1

243. Bukvic, A., A. Smith, and A. Zhang, 2015: Evaluating drivers of coastal relocation in Hurricane Sandy affected communities. *International Journal of Disaster Risk Reduction*, **13**, 215–228. https://doi.org/10.1016/j.ijdrr.2015.06.008

244. Lubell, M., 2017: The Governance Gap: Climate Adaptation and Sea-Level Rise in the San Francisco Bay Area. University of California, Davis, 52 pp. https://environmentalpolicy.ucdavis.edu/sites/g/files/dgvnsk6866/files/2019-10/UC-Davis-Governance-Gap-Sea-Level-Rise-Final-Report.pdf

245. Craig, R.K., 2011: Public trust and public necessity defenses to takings liability for sea level rise responses on the gulf coast. *Journal of Land Use & Environmental Law*, **26** (2), 395–435. http://www.jstor.org/stable/42842970

246. Jones, S.C., T. Ruppert, E. Deady, H. Payne, J.S. Pippin, L.-Y. Huang, and J.M. Evans, 2019: Roads to nowhere in four states: State and local governments in the Atlantic southeast facing sea-level rise. *Columbia Journal of Environmental Law*, **44** (1), 67–136. https://doi.org/10.7916/cjel.v44i1.806

247. Mach, K.J. and A.R. Siders, 2021: Reframing strategic, managed retreat for transformative climate adaptation. *Science*, **372** (6548), 1294–1299. https://doi.org/10.1126/science.abh1894

248. Shi, L., 2020: Beyond flood risk reduction: How can green infrastructure advance both social justice and regional impact? *Socio-Ecological Practice Research*, **2** (4), 311–320. https://doi.org/10.1007/s42532-020-00065-0

Fifth National Climate Assessment: Chapter 10

# Ocean Ecosystems and Marine Resources

# Chapter 10. Ocean Ecosystems and Marine Resources

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# Introduction

The ocean supports diverse and productive marine ecosystems that provide innumerable benefits to the United States. Fishing, recreation and tourism, energy, shipping, and transportation in the ocean and Great Lakes (see Ch. 24) sustain a marine economy that contributed over $781 billion (in 2022 dollars) to the US economy in 2021.[1] Ocean resources support human health and well-being in communities throughout the US, and sustained connections to the ocean are foundational to cultures and identities. This chapter assesses climate impacts and risks to US marine ecosystems, and to the communities and industries that depend on them, as well as ocean-based measures for climate change adaptation and mitigation.

Across the globe, climate change is altering marine ecosystems and connected social systems at a scale and pace that is unprecedented in recent millennia. The combination of long-term changes in physical ocean conditions—such as warming, sea ice loss, acidification, and deoxygenation (KMs 2.1, 3.3)—and short-term extreme events (KM 2.2) such as marine heatwaves threatens marine ecosystems and human communities (Focus on Compound Events). Numerous marine species, from phytoplankton to whales, are altering their distribution, seasonal activities, and behaviors to align with suitable ocean conditions. These changes ripple through the food web, affecting species interactions, ecosystem functions, and biodiversity, as well as conservation, management, and uses of valuable ocean resources.[2] Climate-driven changes to marine ecosystems significantly affect ocean-dependent livelihoods and, in some communities, threaten food supplies and ways of life.[3]

In affected communities, the magnitude of climate impacts and levels of adaptive capacity vary with marine resource dependence, socioeconomic status, and historical and institutionalized inequities.[4,5,6] Some individuals, communities, and industries are adapting to changes, largely through reactionary responses and, in some cases, through coordinated resilience planning.[7,8,9] However, responses are uneven across communities and sectors, and they remain insufficient to meet mounting challenges and costs.[9,10] Global policy choices regarding greenhouse gas (GHG) mitigation govern the intensity and trajectory of future climate impacts and the diversity and effectiveness of adaptation options. Mitigation and adaptation efforts require explicit accountability in social equity, sustainability goals, and fairness in governance and finance to address entrenched inequities that increase climate change risks and adaptation burdens.[5,11]

This chapter draws on global insights to address climate-related changes and challenges in US marine areas. It largely focuses on continental shelf waters, with some discussion of topics that extend shoreward to intertidal areas, and it complements Chapter 9 (Coastal Effects), which extensively covers the topic of sea level rise. The chapter builds upon the climate-related physical oceanographic changes discussed in Chapters 2 (Climate Trends) and 3 (Earth Systems Processes) to highlight some of the unprecedented ecological changes taking place in US marine waters and their impacts on social, economic, and governance systems. Policy directions, planning efforts, and investment decisions being made now will affect mitigation and adaptation options and timelines and will determine the future of our ocean and social and economic systems that rely on it.

## Key Message 10.1

## Unprecedented Climate Impacts Threaten Ecosystems and Human Well-Being

Climate change is significantly altering US marine ecosystems at a pace, magnitude, and extent that is unprecedented over millennia (*very high confidence*). Changes in species locations, productivity, and seasonal timing are cascading through ecosystems, threatening critical connections between people and the ocean (*high confidence*), especially for Indigenous Peoples (*very high confidence*). Risks to marine ecosystems and the people connected to them will be greater under higher scenarios (*likely*, *very high confidence*) and will depend on the ability of ecological and social systems to adapt to the pace of climate change (*very high confidence*). Continued climate change, particularly under higher scenarios, is projected to push many systems toward novel conditions and critical tipping points (*very high confidence*), beyond which the risk of significant impacts to marine ecosystems, including collapse, is high, adaptation may be insufficient, and human well-being is threatened (*high confidence*).

### *Observed Changes*

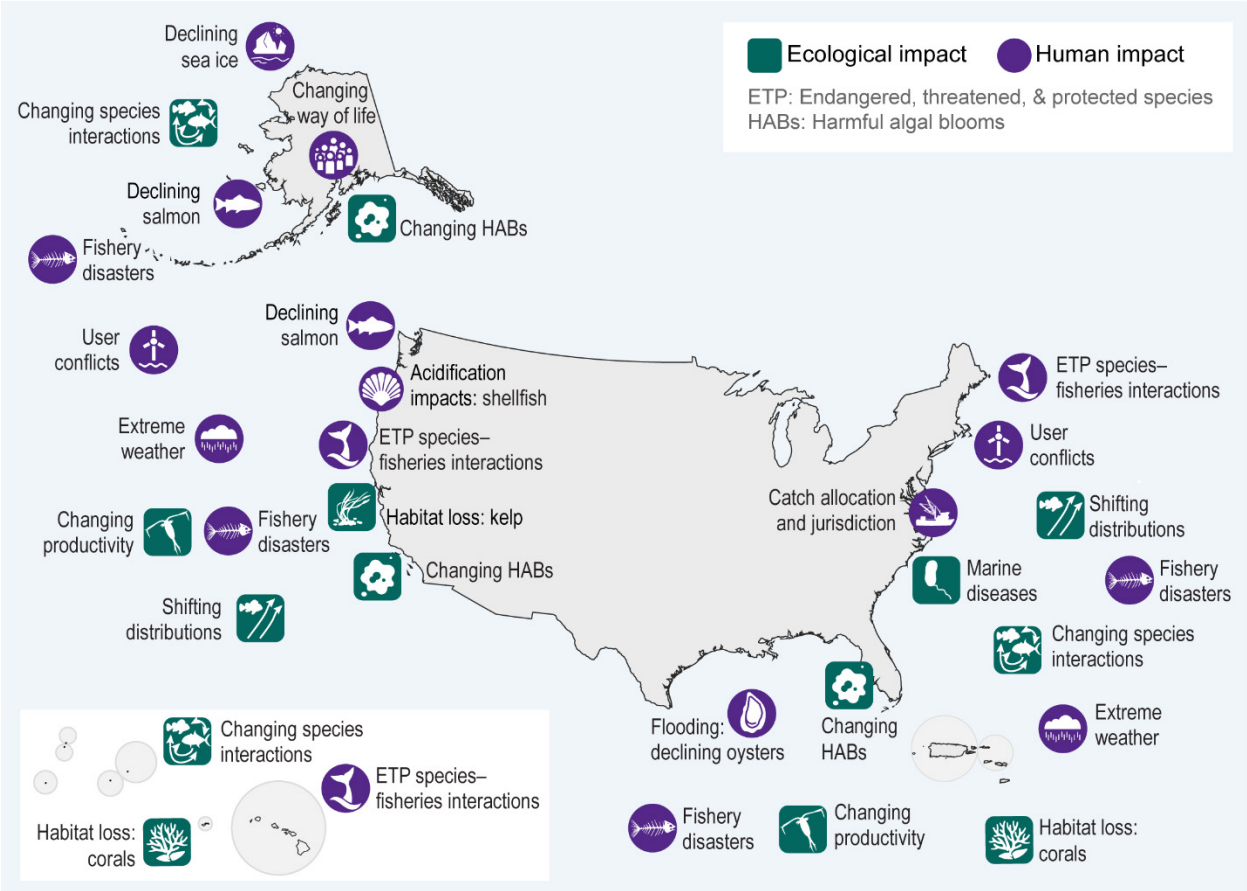
Climate-driven changes are altering marine ecosystems via complex physical, biological, and socioeconomic interactions (Figure 10.1). Many ocean characteristics, such as the timing and length of seasonal cycles, extent and duration of sea ice, oxygen content, and severity of extreme events are exhibiting major divergences from historical patterns (Box 10.1; KMs 2.2, 3.1; Figure A4.11).[10,12,13,14] Changes in distributions, population productivity, and timing of life events are widely documented for marine species and are increasing in prevalence and magnitude (Figure A4.12).[15,16,17,18,19]

Critical habitats such as coral reefs, seagrass beds, and kelp forests have experienced large-scale degradation due to climate-related stressors, threatening their ability to support commercially and ecologically important fish, shellfish, turtles, and marine mammals.[20,21,22,23] Degradation of nursery habitats, spawning areas, and other essential habitats has the potential to affect the productivity and distribution of species.[21,24]

Marine species are shifting their geographic distributions even faster than terrestrial species[25] and are changing the timing of seasonal activities.[16] As changes cascade from microbes to top predators across food webs, these shifts are decoupling some predator–prey relationships[26,27] and amplifying others.[28] For example, shifts in species have reduced prey availability for seabirds, driving large-scale starvation events and breeding-colony failures.[29,30,31]

While warming has benefitted some marine resources in poleward portions of their range (such as an increased abundance of American lobster in the Gulf of Maine[32]), many species—especially those that are cold-adapted, fixed in place, or have complex life histories—have been negatively affected.[33,34,35] Protected and endangered species with limited population resilience, including multiple species of coral, salmon, and whales, are particularly vulnerable to impacts of unfavorable physical and ecosystem conditions (KM 8.2).[22,36,37,38]

## Ocean-Related Climate Impacts on People and Ecosystems




**Many broad-scale climate-related ecological and human impacts are occurring in US marine areas.**

**Figure 10.1.** Climate change is affecting marine ecosystems and impacting human activities in the US ocean. The nature of ocean-based climate impacts is often unique to local areas but can cascade through social–ecological systems to affect the entire country. For example, extreme weather events impact shipping and supply chains, and harmful algal blooms (HABs) in coastal areas affect tourism. User conflicts, such as those involving the siting of offshore renewable energy in fishing areas, have created tensions in US waters. Climate impacts on physical ocean conditions are covered in Chapters 2 and 3. Figure credit: The Nature Conservancy.

Ocean ecosystems are complex and interconnected, making it challenging to fully understand and anticipate climate-induced changes. Climate impacts are less well documented for certain ecosystem components, even ubiquitous organisms such as microbes[39] and pathogens.[40,41] Additionally, climate drivers impacting ocean ecosystems often act in complex ways and, in some cases, can originate on land. For example, altered precipitation patterns over the continental US have both reduced river flow in the Pacific Northwest and increased flooding on the Mississippi, inducing population declines in iconic species such as Chinook salmon[42] and Gulf of Mexico oysters,[43] respectively. Coastal "blue carbon" ecosystems, including coral reefs, seagrass and seaweed beds, mangrove forests, and tidal marshes, are also impacted by interactions between land- and ocean-based changes,[44,45] and these effects can extend to deep-sea ecosystems (Focus on Blue Carbon).[46,47] While US coastal and shelf ecosystems are relatively well studied, the deep ocean (below 650 feet) remains poorly studied.[48,49] The deep ocean stores and absorbs a vast quantity of carbon and heat, buffering the impacts of climate change but also resulting in warming and changes to biogeochemistry (such as deoxygenation) in this portion of the ocean (KMs 2.1, 3.4),[13,49,50] potentially impairing the health of deep-sea ecosystems and the capacity for carbon sequestration.[51]

Ocean climate impacts affect many communities, from coastal inhabitants who make a living from ocean industries to people who live far from the shore and eat fish in the US Midwest or vacation at Gulf Coast beaches. For example, harmful algal blooms (HABs) and increases in pathogens, such as *Vibrio* species, have become more prevalent in some regions, resulting in beach and fishery closures and impacting people's health and livelihoods.[52,53] Effects are amplified for Indigenous Peoples whose long-standing social, cultural, and spiritual connections to the ocean are being altered.[54,55] Subsistence harvests that are critical for food and nutritional security have been disrupted by shifts in species distributions, sea ice loss that limits access to resources, and HABs that make food sources such as razor clams, Pacific walruses, and bowhead whales unsafe for human consumption (KMs 16.1, 29.5).[56,57,58,59,60,61,62,63] Cumulatively, these changes threaten to break vital social and cultural connections by undermining food security and the mental and physical health and well-being of marine resource users.[59,64,65,66]

As impacts of climate change mount, species and people are beginning to adapt. Examples of observed adaptations include species shifting distributions as they track preferred temperatures[67] and subsistence harvesters changing what, where, and when they harvest.[68] The largest and fastest adaptation responses have followed climate impacts that occur as extreme events (e.g., heatwaves, HABs, hypoxia) or that amplify background risks and pressures (e.g., habitat degradation, resource overexploitation; Box 10.1).[69,70]

## *Projected Changes*

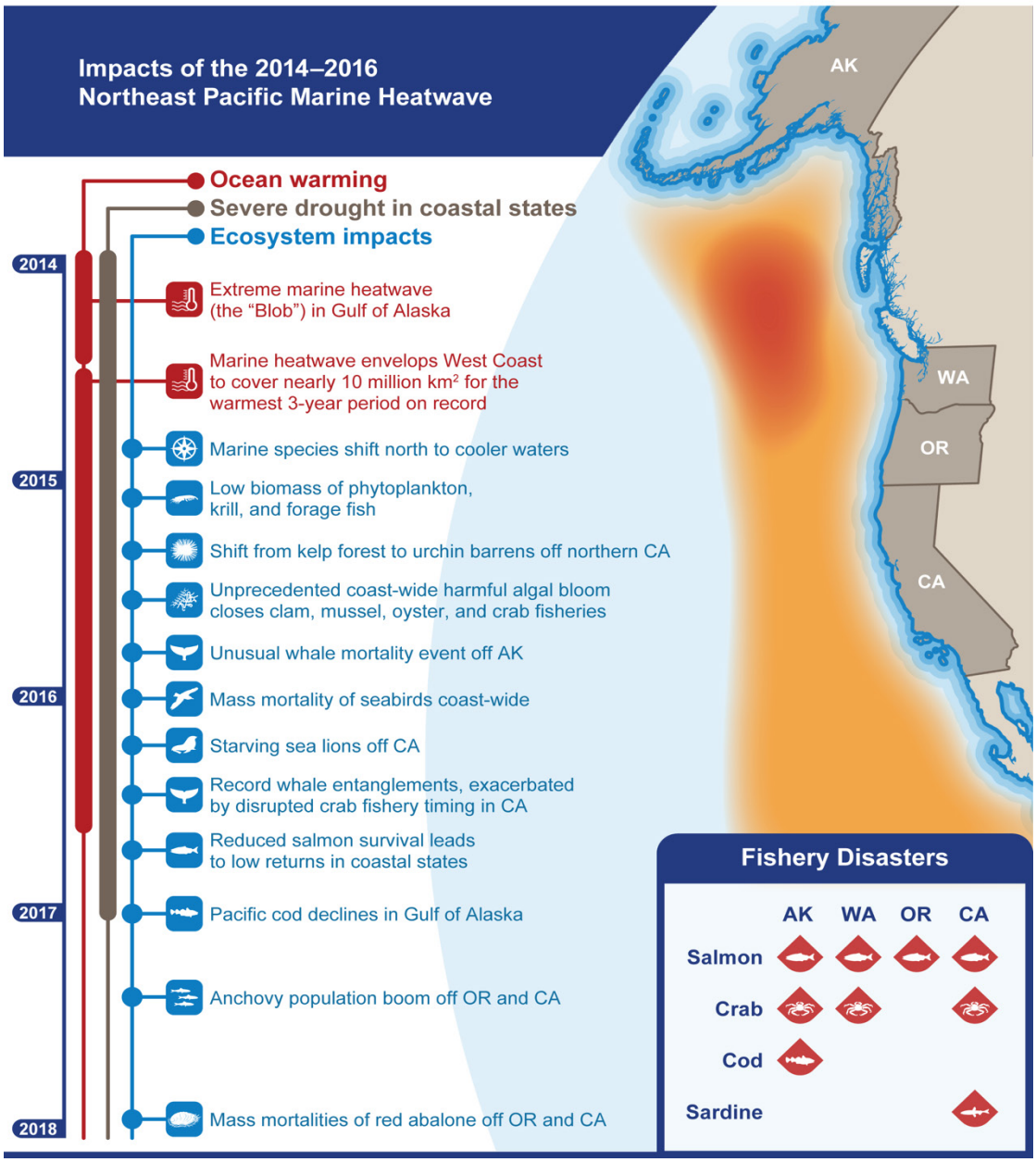
Cumulative GHG emissions will continue to affect marine ecological and social systems over the coming decades. Changes in physical and biogeochemical conditions, including temperature, stratification, upwelling, and ocean chemistry, are projected to become stronger and more widespread, particularly for higher scenarios (KM 2.3),[71] and interactions with chronic stressors such as habitat degradation or overfishing will amplify ecosystem impacts.[10] Shifts in the distribution and biomass of marine species, changes in food web structure and ecosystem functions, and increases in HABs and pathogens will be more pronounced under very high scenarios (RCP8.5, SSP5-8.5).[72,73,74,75] Climate change will drive physical and biological systems toward critical tipping points, triggering feedbacks that may threaten biodiversity, undermine system stability, permanently alter ecosystem functions and services, and limit adaptation options.[76,77,78,79]

Continued climate-driven changes pose challenges for social, economic, and governance systems, particularly those based on expectations that historical conditions will persist into the future. Shifting fish distributions are creating jurisdictional challenges for area-based management, undermining commercial fishery management approaches,[80] and jeopardizing treaty resources such as Tribes' rights to "usual and accustomed" fishing grounds.[81] The severity of impacts to marine social–ecological systems will depend on peoples' ability to adapt at the pace of climate change, which will require participatory governance systems that can effectively and equitably adjust to shifting circumstances.

## Box 10.1. Cascading Impacts of a Marine Heatwave

A massive marine heatwave originated in the Gulf of Alaska in the winter of 2013/14 and subsequently encompassed the US West Coast from 2014 to 2016, producing the region's highest three-year average ocean temperature on record.[82] This event, driven by a combination of natural variability and human-caused warming,[82] had widespread impacts on ocean habitat, marine species, and human communities (Figure 10.2). These cascading impacts are illustrated by a chain of events in which, initially, cool-water habitat was compressed along the coast, causing whales to move closer to shore to feed. This shoreward shift resulted in whales foraging in Dungeness crab fishing grounds and becoming entangled in fishing gear.[83] Meanwhile, the warmer ocean and altered ocean chemistry enabled an unprecedented harmful algal bloom.[61,84] Detection of the neurotoxin domoic acid in marine species closed fisheries, delayed opening of the crab fishing season, and led to multiple fishery disaster declarations.[61] Faced with suspension of the fishing season, fishers were forced to forego revenue or shift to other fisheries;[85] adverse impacts were more pronounced for fishers with smaller vessels, who suffered disproportionately large declines in participation and revenue.[86] Finally, when the Dungeness crab fishing season opened late, increased fishing coincided with the migratory arrival of whales, producing another spike in entanglements.[83] Climate shocks like the 2014–2016 marine heatwave amplify environmental and economic impacts that can linger beyond the event itself.[70] Under future ocean warming, heatwaves will become even hotter, with historically rare temperatures occurring more frequently (KM 2.2). The increasingly novel ocean conditions in the California Current system[87] and other regions will lead to more climate surprises that create challenges for planning and decision-making.[88]

## Northeast Pacific Marine Heatwave Impacts




**The West Coast has experienced unprecedented warm ocean temperatures and environmental disruptions from marine heatwaves.**

**Figure 10.2.** Heatwaves have caused extensive disruptions to marine ecosystems and, in turn, to human communities and economies. Shown here are the widespread impacts of a massive marine heatwave that began in the Gulf of Alaska and subsequently covered the entire West Coast, persisting for several years and coinciding with severe drought over land. Icons on the timeline indicate when impacts occurred; many impacts were sustained for months or years but, for clarity, are shown only at a representative time when they were particularly prevalent. Impacts described as coast-wide or without a specific location occurred off all West Coast states: Alaska, Washington, Oregon, and California. Fishery disasters, as determined by the US secretary of commerce, are shown for individual species (Pacific sardine, Pacific cod) or groups of species (salmon, crab). While the largest heatwave dissipated by 2017, effects of the 2014–2016 heatwave have persisted in the form of lasting ecological changes and new adaptation measures designed to mitigate negative impacts in the future. Figure credit: NOAA Southwest Fisheries Science Center.

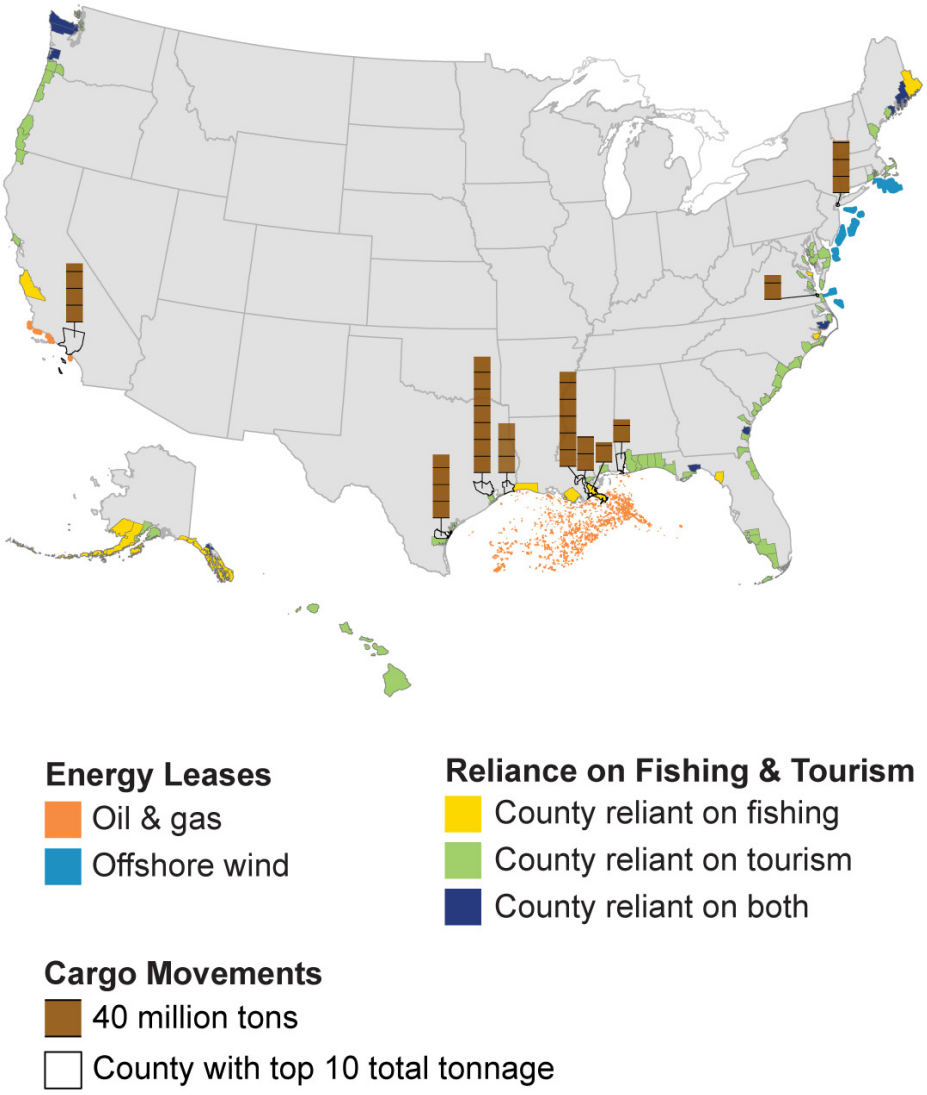
## Key Message 10.2

## Climate Change Is Altering Marine-Related Economic Activities

Climate change poses a substantial risk to ocean-related industries and economic activities such as fisheries, tourism, recreation, transportation, and energy (*high confidence*). As climate change continues, economic and cultural impacts are expected to become larger and more widespread, especially under higher scenarios and in communities that are highly dependent on ocean resources (*very high confidence*). A range of approaches can facilitate adaptation to some degree of climate change (*medium confidence*), but higher levels of climate change will limit the success of adaptation measures and markedly increase climate risk to marine-related economic activities (*high confidence*).

From energy to fisheries to tourism, the ocean economy is deeply intertwined with the economic health of the United States (Figure 10.3). Populations in shore-adjacent counties grew 5.3% from 2010 to 2019, with employment increasing three times as fast (16.3%). From 2005 to 2019, the ocean-related GDP grew by nearly 60% (in constant dollars), representing a total of 3.5 million jobs.[89] Ocean-based activities and industries are being affected by climate change,[90,91] and future impacts may slow growth of the ocean economy. Limiting global warming to 1.5°C (2.7°F) above preindustrial levels confers clear social and economic advantages compared to higher scenarios.[92,93]

## Ocean-Based Economies




**Communities throughout coastal America rely on ocean-related industries for major shares of their local economies.**

**Figure 10.3.** Ocean industries such as fishing, shipping, and tourism are important economic activities in coastal communities across the United States. The Nation's continental shelf is a major source of energy from oil and gas, and renewable energy, particularly offshore wind, is being developed in multiple areas. The ocean-based economy is even more critical to the island commonwealths and territories in the Pacific and Caribbean, although economic data comparable to that for the 50 US states are not available. Economic dependence on ocean resources is proportionately highest in rural communities, which have fewer economic alternatives if they experience climate-related disruptions.[94,95] Figure credit: Middlebury Institute of International Studies, NOAA NCEI, and CISESS NC.

## *Commercial Fisheries*

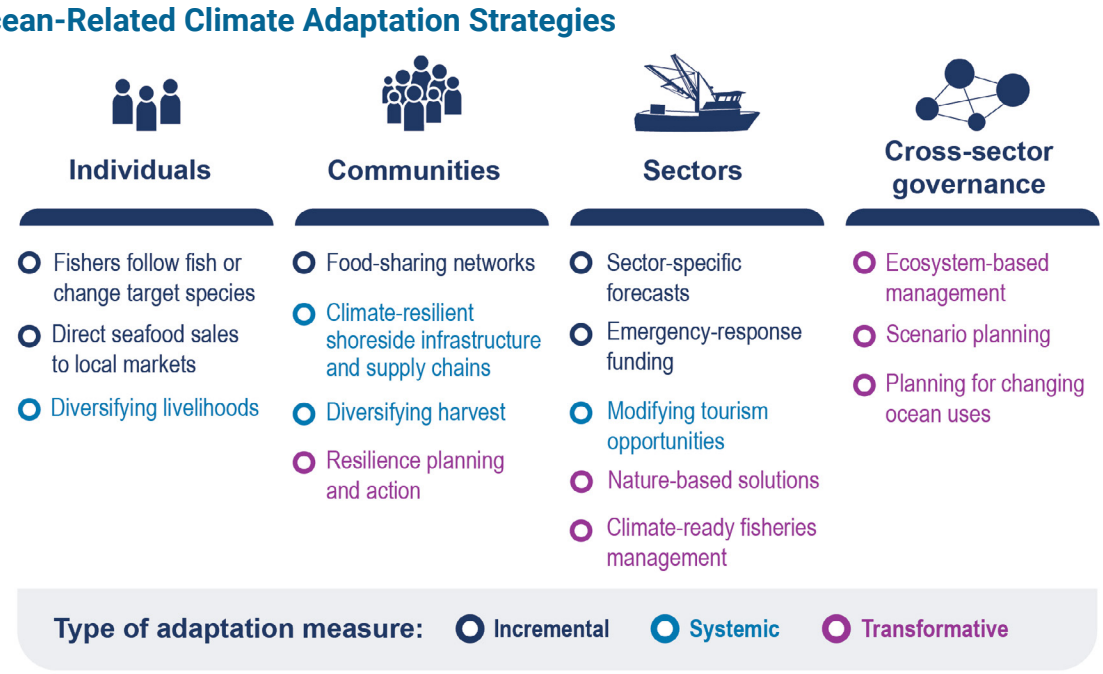
Climate change has impacted commercial marine fisheries in every region of the US by altering the availability and quality of harvested species, destabilizing fisheries-related revenue and employment, and inducing new management challenges.[15,69,85,96,97] The large-scale redistribution of highly valuable Bering Sea (Alaska) Pacific cod and snow crab and subsequent declines in multiple stocks, including closure of the snow crab fishery in 2022, followed low sea ice conditions and protracted warm bottom temperatures across the region (Box 10.1).[98,99,100,101,102] On the East Coast, the northern shrimp fishery collapsed and a fishing

moratorium was imposed following a marine heatwave in 2012,[103] and the highest-valued single-species fishery in the US, American lobster, has seen the southern portion of its population decline to very low levels with warming waters.[32] Disaster declarations for commercial fisheries increased markedly from 1994 to 2019, with more than 84% of fishery disasters linked to extreme environmental events, totaling $3.4 billion of lost revenue and $2.3 billion (in 2022 dollars) in federal funding for disaster relief.[104] Recent climate-related fishery declines have been widespread,[85,105,106] although a few stocks have increased with ocean warming and heatwaves (e.g., regional increases in the northern stock of American lobster, market squid, and sablefish[32,107,108]). While climate is not the sole driver impacting fish populations, it is an added stressor that exacerbates other negative impacts.[33]

Over the next century, climate change is expected to reduce catch in all US regions,[92] including some of the highest-valued fisheries (e.g., Bering Sea snow crab, walleye pollock, Pacific cod, American lobster, and Atlantic sea scallops[32,109,110,111,112]). For 16 species that represent more than half of commercial fisheries revenue, climate-induced changes are projected to result in billions of dollars of economic losses by 2100, with losses twice as high under a very high scenario (RCP8.5) than an intermediate scenario (RCP4.5).[113] Many species will continue moving northward and deeper, reducing accessibility for subsistence harvesters and smaller vessels and complicating management policies and quota allocations.[114,115,116,117,118] Severe storms and sea level rise will increasingly threaten shoreside infrastructure and transportation networks that are critical for harvesting and distributing seafood products (KM 9.1).[4,119]

Climate impacts are not distributed equally across all fisheries and can be compounded by non-climate factors, including fisheries management, market conditions, socioeconomic conditions, and external shocks (e.g., COVID-19).[4,86,115,120] Impacts are generally greater for small-scale coastal harvesters who are less able to follow shifts in fish distribution or who have access to a limited number of fish stocks, while those with larger vessels and more diverse harvest portfolios are generally more resilient.[85,86,118,121] Commercial fisheries and subsistence harvesters are adapting to these changes through short-term incremental measures, business investments appropriate for changing conditions, and management efforts supporting climate-ready fisheries (Figure 10.4).[96,122,123]

The effectiveness of future adaptation responses may be limited by the magnitude of change and factors like inequities in finance and governance across communities, costs of equipment or infrastructure, and access to fishing permits (Focus on Risks to Supply Chains).[80,97,115,124] As fisheries adapt, community initiatives such as permit banks and seafood cooperatives that plan for climate change can enhance equitable opportunities and socioeconomic benefits (Figure 10.4).[125,126] Diversifying harvest and livelihoods, including expanding into marine aquaculture (KM 11.1), can also help stabilize income or buffer risk. Tools that predict species distribution changes can help avoid bycatch, reduce costs, and increase yield.[127] Further, ecosystem-based and climate-informed management can align harvest limits with population productivity to maintain sustainable fishing levels.[109,110,128]




**Adaptation can occur at many organizational scales—from individuals to governance systems.**

**Figure 10.4.** Many types of adaptation measures are being undertaken, or are under consideration, as ways to respond to and prepare for climate change impacts on ocean activities and economic sectors. The measures range from small adjustments (incremental) to larger actions within current socioeconomic and management systems (systemic) and substantial changes beyond existing systems (transformative). Figure credit: Gulf of Maine Research Institute.

## *Tourism and Recreation*

Ocean-based tourism and recreation—the largest sector in the ocean economy, representing $274.5 billion of economic activity in 2021 (in 2022 dollars)[1]—is both positively and negatively impacted by climate change.[129] Warming temperatures extend the coastal tourism season, yet sea level rise threatens shoreside facilities (KM 9.2) and will change nearshore wave dynamics in ways that reduce or eliminate some surfing opportunities.[130] In the Gulf of Mexico and Caribbean, worsening HABs[131] and blooms of macroalgae (e.g., *Sargassum*[132]) due to climate and local non-climate stressors have raised human health concerns (KM 23.1) that have disrupted tourism and fishing.[133,134] Recreational fisheries are experiencing climate-related changes in anglers' participation, location choices, and expenditures.[135] As warming continues, angler participation may decline by up to 15%, with losses as high as $413 million annually (in 2022 dollars) along the Atlantic and Gulf of Mexico Coasts; however, warming is increasing participation in some areas (e.g., New England).[136]

Similarly, tourism impacts are different across regions. Arctic sea ice loss is creating tourism opportunities by allowing "last-chance" cruise ship tourists to see ecosystems before they are further altered by climate change.[137] However, coral reef tourism—valued at nearly $3 billion annually for 2008–2012 (in 2022 dollars) in Hawai'i and Florida—is threatened by bleaching and disease that deter divers and snorkelers (KMs 23.3, 30.4).[138] At a more localized scale, the loss of endangered southern resident orca whales in Washington's Puget Sound due to climate-driven declines in food would result in annual losses of $39 million in economic activity (in 2022 dollars).[36,139]

## Transportation

Climate change is already affecting marine transportation. Sea ice loss and longer open-water seasons have enabled transit between the Atlantic and Pacific via the Arctic, with ship traffic in the Arctic increasing threefold between 1990 and 2015,[140,141] and Arctic-routed shipping continues to be considered.[142] With 3.6°F (2°C) of warming above preindustrial levels, ships are projected to be able to reliably navigate the Northwest Passage and Arctic Bridge trade routes in summer.[143] These routes may reduce carbon emissions and shipping costs, but concerns exist about impacts to marine species and local communities, as well as about black carbon emissions.[54,144,145,146]

Commercial vessel emissions have increased over time, as has the sector's proportional contribution to global emissions (KM 13.1),[147] but emissions from recreational boats in the US declined between 1990 to 2021.[148] The shipping sector is initiating further measures to reduce its GHG emissions by powering docked vessels with electricity,[149] increasing vessel efficiency to reduce global shipping emissions by 50% by 2050,[147] and planning for some zero-emissions maritime routes by 2025.[150]

## Energy

Ocean-based energy production in the US is in a period of transition. Ocean-based energy has been almost exclusively derived from hydrocarbon extraction, which generated $96.4 billion in 2021 (in 2022 dollars).[1] Globally, nearly 30% of commercially recoverable oil and gas assets are found in areas at high risk for climate impacts.[151] In the US, stronger hurricanes, increasing wave heights, and sea level rise will threaten offshore facilities and associated coastal structures, such as underwater pipelines and refineries (KM 9.2).[152,153] Facilities may increasingly require adaptive responses, such as raising the height of oil and gas platforms in the Gulf of Mexico to reduce hurricane damage.[154,155]

Renewable energy sources are expected to increase as part of the ocean-based energy mix over the next several decades. The first US facilities to generate electricity from ocean wind are in place off the Atlantic Coast, and in 2021, the US set a goal of installing more than 30 gigawatts of capacity by 2030, enough to power about 10 million homes.[156] States have set additional goals for offshore wind energy development that may further advance this capacity. Through 2022, more than two million acres of ocean bottom have been leased for wind energy, with more leases anticipated by 2025.[157] The growth of ocean-based renewable energy is expected to bring jobs and economic benefits to certain coastal communities, but its ecosystem impacts are still being determined, and its development may constrain other ocean uses, including fishing, transportation, and aesthetic preferences.[158,159,160,161,162]

## Key Message 10.3

## Our Future Ocean Depends on Decisions Today

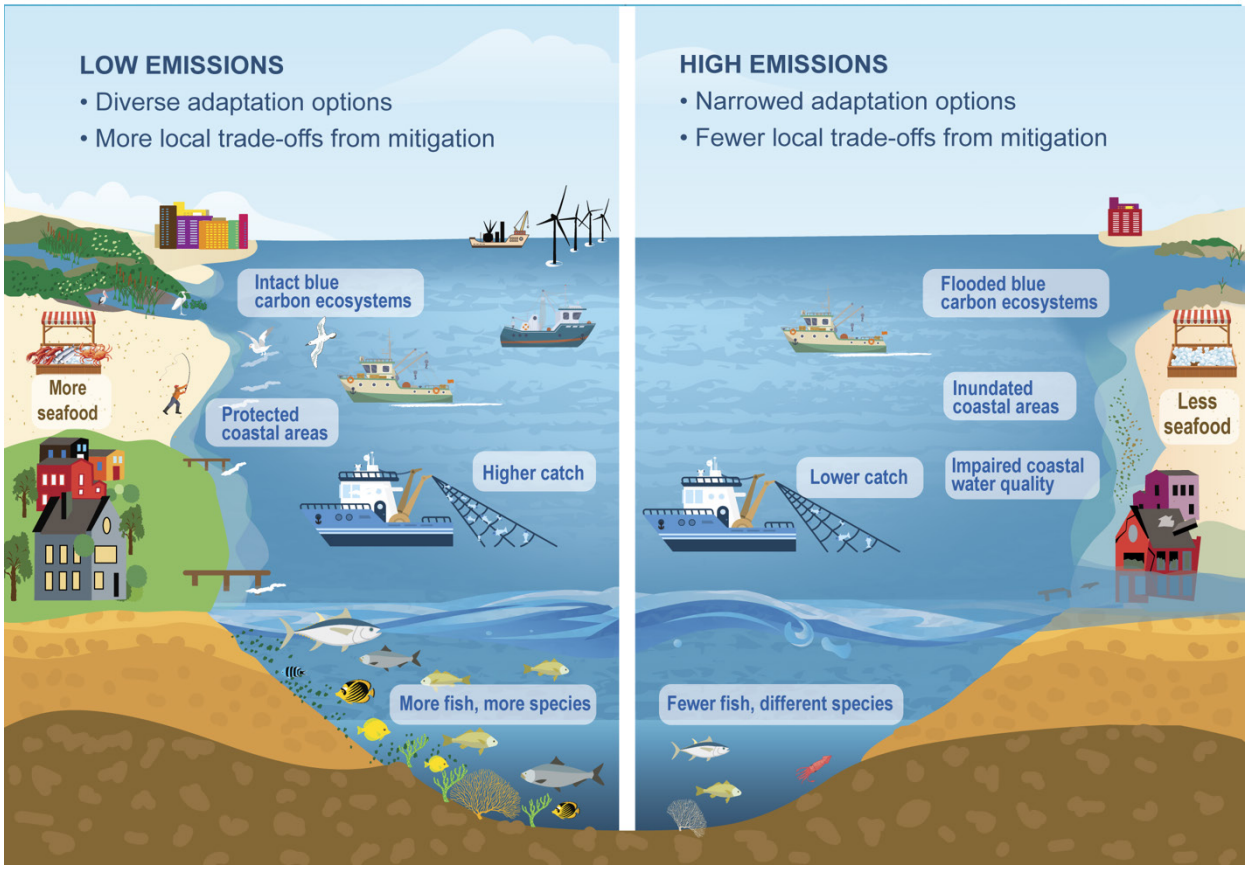
Future risks to marine ecosystems, ocean resources, and people will be substantially reduced by implementing adaptation and mitigation actions now (*very high confidence*). Responding swiftly to climate change will improve outcomes, reduce costs, promote resilience and equity, and allow the widest possible suite of adaptation solutions (*very high confidence*). Impacts will continue to be uneven across communities, with more harmful outcomes in communities that are highly ocean-reliant and historically marginalized, unless equitable adaptation and mitigation efforts are implemented (*high confidence*).

### *Current State of Ocean-Based Adaptation and Mitigation*

Although substantial climate-driven changes in ocean ecosystems are inevitable over the coming decades (KM 2.3), the future of these systems, their valuable services, and the businesses, communities, and economies that depend on them will be determined by the choices we make now on mitigation of GHG emissions and investment in adaptation measures (Figure 10.5). Proactive, coordinated, large-scale approaches to planning, financing, and implementing adaptation measures are necessary to achieve effective and equitable outcomes (KM 31.2).[10] Reactive actions to cope with climate impacts are occurring at individual, business, and community scales but are largely uncoordinated and sometimes ineffective (Figure 10.4). Adaptive capacity is not the same across communities or groups; communities that are highly reliant on ocean resources may face the greatest risks and be constrained by socioeconomic factors, historical and ongoing inequities, and access to governance systems or financing.[4,5,163] Promising proactive adaptation-planning measures are starting to emerge in various regions and sectors. For example, some state and federal fishery-management bodies and stakeholder communities have prioritized climate preparedness and are developing information, tools, plans, and processes to address future changes and uncertainty in marine resources and fisheries.[164,165] Certain municipalities and Tribal communities are pursuing integrative climate resilience planning that considers adaptation needs across multiple ocean-related sectors (e.g., Cities of Portland and South Portland 2021;[166] Takak et al. 2021[167]).

Various ocean-based mitigation approaches are also advancing.[168] Measures to protect and restore marine ecosystems that capture and store carbon dioxide—such as mangroves, seagrasses, and kelp forests—are underway and offer additional benefits like wave energy dissipation and fisheries enhancement, but carbon mitigation benefits may be modest and variable (Focus on Blue Carbon).[10,169] Public- and private-funded projects are evaluating technical, economic, and social dimensions of ocean-based carbon dioxide removal techniques (KM 32.3; Focus on Blue Carbon).[170,171,172,173,174] Ocean-based wind energy is being implemented (KM 10.2) and wave energy conversion is being developed, especially in the Pacific basin.[175] Electric and hybrid engines for small boats[176] and expanded production of aquatic foods with lower GHG emissions[177] also support ocean-based mitigation. Estimates suggest that fully scaled-up ocean-based mitigation measures would provide about a quarter of the atmospheric GHG reduction required to meet global pledges by 2050.[172,176,178]

### Ocean Conditions and Activities Under Two Climate Scenarios




**Future ocean conditions and activities will depend on emissions levels and mitigation strategies.**

**Figure 10.5.** Future marine ecosystems and human activities will differ under low versus high greenhouse gas emissions scenarios. This figure is a simplified depiction of major predicted changes as a result of climate change. Under low scenarios (**left**), more adaptation options remain available, and ocean services such as food provision and coastal protection are maintained, but trade-offs between ocean-based activities will escalate. Under high scenarios (**right**), ecosystems will be altered, fewer adaptation options will be available, and losses of services are expected across diverse sectors. Figure credit: Center for American Progress and Gulf of Maine Research Institute.

## *Challenges and Trade-Offs*

Immediate implementation of ambitious mitigation and adaptation measures offers the greatest chance of maintaining ocean ecosystems and their benefits to people, as well as supporting equitable human development.[10] Carbon emissions peak in the mid-2020s in scenarios that limit warming to less than 3.6°F (2°C), above which risks and impacts are projected to rapidly increase across sectors and regions.[179] Without carbon mitigation, estimates indicate that a critical global warming threshold of 2.7°F (1.5°C) will be crossed in the 2030s.[179]

Coordinated adaptation planning is essential to ensure that strategies across sectors, communities, and regions are complementary and achieve equitable outcomes. Adaptation and mitigation options tend to be most successful if they are based on sound information, developed in collaboration with local communities and diverse actors, and designed to lower ecosystem and community risk.[10,180,181] Although adaptation measures are already being taken in some areas (KM 10.2), the ability to adapt is uneven across groups, communities, and sectors (KM 31.2). People with socioeconomic assets such as strong social connections,

alternative livelihood options, and economic wealth are more resilient to climate disruptions,[6,85,86,182] and those with greater access to information and other resources will be better positioned to engage in adaptation efforts. Participatory planning, financial, and governance processes designed to account for divergent power dynamics and institutionalized discrimination can engage a broad array of community members in co-producing climate solutions.[181] Deliberately incorporating local knowledge, perspectives, and values can help determine efficient, enduring, and equitable adaptation and mitigation solutions.[8,180,181]

Effective climate change adaptation in marine systems also depends on implementation of carbon mitigation. Without emissions reductions, the range of possible adaptation options decreases substantially. For example, adaptation options in coral and mangrove ecosystems include reducing non-climate stressors such as pollution and prioritizing effective harvest management and habitat restoration. With increased emissions, these measures will become insufficient to maintain coral and mangroves due to warmer, more acidic conditions, and adaptations will be limited to more expensive, higher-risk options such as active translocation of species, assisted adaptation, or reef shading.[183,184] As emissions increase and the range of options for maintaining these habitats decreases, the risks of losing services they provide, such as coastal protection, livelihoods, food security, cultural identity, and tourism, are magnified.[10]

Adaptation measures with co-benefits for mitigation are especially promising. These include reef and marsh restoration, seaweed aquaculture, ecosystem-based management, and marine spatial planning. Nature-based solutions have the potential to be cost-effective and self-reinforcing over time, and if implemented at scale, they may impart climate, societal, and ecological benefits for adaptation and carbon mitigation.[185,186,187] Solutions that include equity and diversity targets and are designed through inclusive and participatory approaches have the greatest potential to both address ongoing injustices and impart benefits for marine resource users and Indigenous communities.[180,188]

Emerging technologies could further expand ocean-based mitigation, but significant uncertainties must be resolved. Research projects are exploring the design, manufacturing, and grid integration of wave, thermal, and tidal energy-capturing devices.[189] Electricity and scalable zero-emission fuels such as hydrogen are being evaluated for decarbonizing oceangoing vessels.[190] All ocean-based carbon dioxide removal techniques still require substantial research on scalability, durability of carbon storage, environmental and social impacts, governance, and financing, as well as development of suitable regulatory frameworks.[169,172,191]

Trade-offs among adaptation and mitigation activities, ecosystems, and social systems may become more challenging as more options are deployed. Ocean-based mitigation measures such as offshore wind or carbon dioxide removal could have environmental and economic impacts.[161,192] Mitigation infrastructure may affect existing activities, including fishing, boating, and shipping—which are themselves adapting to climate change.[193] Decision-making about mitigation and adaptation choices—for example, those around disproportionate environmental burdens borne by historically marginalized racial and ethnic groups or communities with fewer economic resources—also poses ethical challenges.[194] These ethical challenges may be greater for actions related to the ocean, given its complex governance systems.[195]

## *Needs and Opportunities*

Ocean-related efforts to mitigate and adapt to climate change generally lag terrestrial efforts for several reasons, including gaps in ocean observations, lack of robust forecasts and projections, and limitations in mechanistic understandings of underlying climate-related changes. The ocean sector also faces challenges related to missing tools and services for adaptation, sector-specific (or siloed) management and governance, insufficient financing, and divergent stakeholder goals.[10] Providing equitable access to information from scientific research and local knowledge, promoting evidence-based planning and adaptive management, and implementing actions to address near- and long-term risks can help prepare for climate impacts to marine ecosystems and resources.

## Data and Research

Effective and cost-sensitive responses to changing oceans entail tracking changes in social–ecological systems and using that information to address risks. Strategic expansion and coordination of ocean observations and long-term monitoring programs (inclusive of community science) are necessary to document changes across marine ecosystems.[196,197,198,199] Indigenous and local knowledge of ecosystem changes can be more fully integrated with other knowledge sources to support decision-making for ocean ecosystems.[180,200,201] Key limitations remain in tracking, understanding, and projecting changes in marine ecosystems and impacts on people and economies. In particular, limited data are available in the US Caribbean and US-Affiliated Pacific Islands. Moreover, few coordinated monitoring and information-development efforts span regional or international boundaries.[202]

Climate-relevant economic and social data are not available at temporal and geographic scales necessary for tracking how climate change impacts on the ocean affect people. Socioeconomic data, such as the number of people using the ocean for recreation, are lacking or exist only at large geographic scales that do not support analyses of local impacts or evaluation of the effectiveness of adaptation strategies.[203,204] Further, the lack of socioeconomic data precludes efforts to understand disparate impacts of and responses to climate change on communities of different sizes and income levels.

## Data-Informed Management and Adaptation

Responses to climate impacts are most successful when they incorporate robust scientific information into decisions, which can be supported by research and products that are designed with end users.[205] Increased data accessibility and technical expertise focused on interpreting climate impacts and adaptation effectiveness will facilitate novel research and help deliver information that is relevant to decision-makers and stakeholders. Continued advances in near-term to decadal forecasts are urgently needed to provide decision-makers with early warnings and shape options that are incorporated into response plans, particularly for extreme events such as marine heatwaves, coral bleaching, HABs, or fish population changes.[206,207,208,209,210] Mid- and longer-term projections of changes in ocean ecosystems are necessary to support risk assessments and strategic planning.[211,212] Development of operational ocean modeling and decision support systems is a promising step to provide decision-makers with science-based information to implement adaptation measures.[122,210]

## Governance and Financing

The extent of future climate impacts will depend both on the nature and magnitude of climate-related changes and on the degree to which individuals, businesses, communities, and governments can adapt to those changes.[213] The pace, scale, and scope of expected climate impacts on ocean ecosystems necessitates assessing the ability of existing governance and management frameworks to effectively respond. There is also a need for financial incentives to develop and implement mitigation and adaptation actions, including support for community and sectoral adaptation. Adaptation and mitigation choices inevitably result in trade-offs that affect possible outcomes, implementation costs, and entities that bear the costs or receive the benefits.[168] Inclusive and participatory frameworks for evaluating these trade-offs will support equitable deliberations about potential outcomes and uncertainties surrounding specific options. Such processes are especially critical for Indigenous communities with strong sociocultural connections to marine ecosystems and subsistence harvesters who rely on marine resources for food, nutritional, and economic security.[5,214] Adaptive governance systems and cross-sector, cross-scale coordinating mechanisms can help advance actions that are acceptable to multiple stakeholders.[213]

# Traceable Accounts

## *Process Description*

### Author Selection

Chapter leadership considered suggestions from the Federal Register Notice process and their own networks to identify authors with topical expertise, geographic familiarity, and disciplinary perspectives that span many issues relevant to the chapter. The goal was to build a diverse team in terms of racial, ethnic, and gender diversity; career stage; involvement in past climate assessments; and representation from the academic, governmental, and nongovernmental sectors. Seventeen invitations were issued, from which a team of eight authors was assembled, including physical scientists, marine ecologists, fishery scientists, economists, and policy analysts with experience assessing climate impacts on marine ecosystems, fisheries, marine economies, and coastal communities. Authors also have expertise in conservation approaches, adaptation strategies, and management measures that may buffer climate change impacts, and several authors are engaged in research and policy analysis related to ocean-based climate mitigation options.

### Literature Review and Public Engagement

Chapter authors reviewed the Fourth National Climate Assessment (NCA4) "Oceans and Marine Resources" chapter[215] and brainstormed topics for NCA5 that had emerged since then or were not well covered in NCA4. The chapter lead identified additional topics from the US Global Change Research Program (USGCRP) assessment review document and public comments. The importance of certain topics was reinforced and additional topics were identified during three public engagement workshops organized by USGCRP (January 25, 2022), the American Fisheries Society (February 1, 2022), and the Ocean Sciences Meeting (February 24, 2022). Initial topics were subsequently honed through agency review and public input. The author team routinely reevaluated the literature to incorporate scientific advances into the assessment and prioritize topics that could be covered within the space limitations.

### Decision-Making Process

The chapter team held biweekly to weekly videoconferences to hone the chapter's topics, Key Messages, and supporting information based on discussions of the state of the science. Small groups of authors developed text associated with each Key Message based on their expertise, literature review, and stakeholder input. The full author team reviewed each Key Message and its supporting information, and revisions were made until the team was satisfied with the text. The lead author administered a survey to elicit detailed input from each author on the high-level Key Message statements and the associated confidence and likelihood ratings. Differences in phrasing and ratings were discussed among the author team, and revisions were made until the group reached consensus on the content of those statements.

## Key Message 10.1

# Unprecedented Climate Impacts Threaten Ecosystems and Human Well-Being

### Description of Evidence Base

A robust body of evidence shows that climate change is having major impacts on US marine ecosystems. Changes in physical and chemical ocean conditions (Chs. 2, 3)[10,12] affect species through distribution shifts, productivity changes, and phenology alterations.[15,16,18,19] In shallow-water habitats (coral reefs, seagrass beds, and kelp forests), climate-related declines have been documented,[20,22] but limited evidence is available to assess impacts in the deep sea.[49] In certain places (e.g., Arctic and coral reef habitats), thresholds are being reached, beyond which ecosystem functions will be eroded and systems will be permanently altered.[22,58]

Evidence documenting climate impacts on marine-dependent human communities and alterations in cultural and social interconnections, economies, and livelihoods is growing. Climate-driven ecosystem changes threaten critical social couplings that underpin the well-being, subsistence, and economic and cultural identities of many communities with strong ties to the ocean, particularly coastal and island-based Indigenous communities (KMs 29.5, 30.5).[54,163] Climate change has profoundly impacted Indigenous harvest of marine species, including those critical for subsistence.[54,56,60,62] Indigenous Knowledge continues to reveal the breadth of climate impacts on human health, ecosystems, and subsistence resources, as well as the effectiveness of adaptation measures.[57,62,63]

Evidence of future ecological and social impacts draws on climate projections to extrapolate contemporary responses into the future. Model projections show consensus on the direction of many physical and chemical changes (e.g., warming temperature, declining pH; KM 2.1).[179] Based on observed responses of species to environmental conditions and known physiological limits, populations and distributions are expected to be substantially altered by climate change.[10,72,75,78] Impacts of marine ecosystem changes on humans are expected to increase as the conditions depart further from past conditions, although the magnitude depends on the rate of change and capacity for adaptation.[213]

### Major Uncertainties and Research Gaps

While overall physical and biological trends are well characterized and projected to continue, the exact scale, timing, and location of future impacts are uncertain. Uncertainty in the scale of impacts derives primarily from unclear future socioeconomic pathways (including greenhouse gas [GHG] emissions). Spread among models on the sensitivity of Earth's climate to socioeconomic futures (KM 2.1) and, in some cases, inadequate model resolution to forecast local-scale effects also contribute to uncertainty.[212] While the severity of extreme events will increase as natural variability occurs on top of a changing baseline (KM 2.2), we do not know exactly when or where extreme events will occur. Thus, the continued development of prediction systems is a priority to extend the lead time of extreme event warnings (e.g., Tommasi et al. 2017;[210] Jacox et al. 2022[206]).

Biological and ecological impacts of climate change, such as shifts in species distributions, can be assessed based on past observations. However, many existing observation systems were not deployed until recent decades,[199] with the deep ocean remaining particularly under-observed.[216] There is uncertainty associated with models of physical–biological relationships and challenges in scaling climate change impacts at the individual level to population dynamics, community interactions, or ecosystem functions. Data and studies of ecosystems and coupled social–ecological systems become scarce at large or complex scales.

Research gaps increase across the spectrum of complexity, from physical changes to system-level ecological and human impacts.[10] Baseline studies vary widely for ocean ecosystems and regions. For example, coastal ecosystems are much better observed and studied than the deep ocean, and US regions with the strongest

climate signals or occurrence of extreme events (e.g., Alaska, Northeast, West Coast) have been more extensively studied than other regions. Few studies are available for assessing climate impacts to marine ecosystems, resources, and communities in non-continental US regions, such as Hawai'i and the US-Affiliated Pacific Islands and the US Caribbean.

### Description of Confidence and Likelihood

For most elements of this Key Message, the authors have decided not to assign likelihood ratings, as quantitative projections of the impacts discussed are typically focused on a specific species, process, or ecoregion. Scaling likelihoods from these focused studies up to a general message is difficult. Statements of likelihood are scenario-dependent, and studies may not use the same scenarios or compare scenarios, which limits a consistent evaluation of likelihood.

The large and growing literature on climate impacts in marine ecosystems, coupled with attribution studies demonstrating that human-caused climate change is driving ocean conditions beyond the envelope of historical variability, give *very high confidence* that we have entered an unprecedented period of climate-driven marine ecosystem change.[179,213] Studies of biological responses to climate change are widespread, but there is somewhat less research documenting how the cascading impacts of physical and ecological ocean changes affect human communities. The available information indicates that impacts are predominantly neutral or negative, leading to *high confidence* in our understanding of impacts to livelihoods, cultures, food supplies, and other human-ocean connections.[10] A number of studies have focused on impacts to Indigenous Peoples, indicating *very high confidence* that climate change is altering ways of life, cultural traditions, and connections to the ocean for many Indigenous groups.[54,58,68] The scientific literature overwhelmingly projects that climate-driven changes in social–ecological systems will become more frequent and intense as human-caused climate change emerges further from natural climate variability, with the greatest impacts under high or very high scenarios.[72,75] Because a large evidence base consistently projects higher risks to marine ecosystems under higher scenarios, this outcome is considered *likely*, with *very high confidence*. While there is uncertainty about the pace and effectiveness of adaptation in social–ecological systems, there is *very high confidence* that the risks will be elevated if the pace of adaptation does not match or exceed the pace of climate change. The existence of ecological tipping points is supported by theory and empirical evidence (e.g., Hoegh-Guldberg et al. 2019;[77] Stewart-Sinclair et al. 2020;[79] Penn and Deutsch 2022[78]), and the authors have *very high confidence* that many systems are moving toward tipping points and that some will be crossed in the future. This confidence is highest in ecosystems such as coral reefs that are experiencing frequent bleaching events and die-offs[10] and in the Arctic, where declining sea ice is altering the ecosystem and social–ecological connections (KM 29.5). The authors have *high confidence* that as ecosystems move toward tipping points, interconnected social systems will be fundamentally changed in ways that threaten the well-being of people and communities.[76]

## Key Message 10.2

## Climate Change Is Altering Marine-Related Economic Activities

### Description of Evidence Base

Studies characterize the observed and projected impact of climate change on US commercial marine fisheries. These include temperature impacts on productivity and redistribution of species and dependent fisheries, communities, supply chains, markets, and fisheries management.[15,69,85,96,97,100,118,121] Commercial fisheries and subsistence harvesters are adapting to these changes through shifts in fishing locations, target species, harvest diversification, and other strategies, yet adaptive capacity varies across different types of harvesters and communities.[68,85,118,163] Projections of how climate change will affect fisheries are available

for many of the largest US commercial fisheries (e.g., Rheuban et al. 2017;[111] Le Bris et al. 2018;[32] Holsman et al. 2020;[110] Moore et al. 2021[113]). However, the magnitude of impacts differs across models that vary in resolution, complexity, and inclusion of regional management measures.[109,217]

Several studies characterize temperature- and weather-driven changes to human behavior around tourism and recreation,[130,135,136] as well as direct impacts to resources that drive tourism.[36,138,139] The data needed to quantify impacts and benefits of mitigation efforts in the transportation sector are more limited, although there has been a strong focus on the Arctic.[54,60,140,143] Sea level rise will also threaten ocean transportation and shoreside infrastructure (KM 9.2).

Studies have determined that climate change, particularly sea level rise and stronger storms, poses a direct threat to ocean-based oil and gas infrastructure,[155] as well as an indirect increase in the risk of oil spills due to climate change.[154] For offshore wind, studies have estimated production capacity and variability off the US coasts and described potential impacts to surrounding ecosystems[161,192] and existing ocean uses.[158,160,162]

## Major Uncertainties and Research Gaps

Scientific literature associated with climate impacts and adaptive responses in ocean-based industries is developed and growing for commercial fisheries but is limited for many other sectors. Although tourism represents the largest sector of the ocean economy, there are relatively few studies that project climate impacts to the US ocean tourism sector at regional to national scales. Those that are available focus on specific industries in specific locations, such as cruising in the Arctic,[137] coral reef tourism in Florida and Hawai'i,[138] and whale watching in Puget Sound.[139] Studies of climate impacts on marine recreational fisheries are also limited,[135,136] particularly compared to extensive studies of commercial fisheries. Efforts to reduce GHG emissions from vessels, ports, and shipping are developing,[147,149] but limited data availability makes it difficult to track associated implementation progress and emission outcomes. Syntheses of the state of knowledge related to ecological, economic, and community impacts of the development of ocean-based renewable energy are just recently becoming available.[159]

The greatest limitation in understanding economic and social impacts of climate change on marine-dependent livelihoods stems from the lack of publicly available economic and social data—specifically at spatial and temporal scales necessary to track changes, measure impacts, and make projections for marine economic sectors.[218] This gap constrains efforts to quantify the magnitude of impacts, effectiveness of adaptation strategies, and differential impacts and responses across distinct groups. A nascent area of study concerns the interacting and compounding ecological, social, economic, and cultural impacts of changes on the social–ecological systems with which marine industries interact.

## Description of Confidence and Likelihood

Across numerous studies, there is high agreement and robust evidence, and therefore *high confidence*, that climate change poses significant risk to marine economic sectors and activities. This evidence includes various determinations of climate change risk from recent assessment reports with focused chapters on marine sectors and communities (e.g., Constable et al. 2022;[219] Cooley et al. 2022;[10] Hicke et al. 2022[7]). Multiple studies have evaluated risk over time under contrasting future carbon mitigation scenarios; high agreement in results yields *very high confidence* that climate change impacts increase over time and with higher levels of global warming, posing higher risks to communities and groups that have fewer economic alternatives and lower adaptive capacity.[179,213] The impacts of ocean-based climate change depend on the effectiveness and feasibility of adaptation measures that remain largely nascent,[10] leading to *medium confidence* that adaptation measures can help reduce the impacts of climate change. Adaptation options narrow and challenges of adaptation increase with greater magnitude and complexity of impacts,[7,10] giving *high confidence* in the limits of adaptation under higher scenarios. Quantitative projections of climate

impacts on marine economy sectors are few and location-specific, and they do not use multiple or comparable climate scenarios; as such, the authors have decided not to apply likelihood ratings.

## Key Message 10.3

## Our Future Ocean Depends on Decisions Today

### Description of Evidence Base

There is abundant evidence that the severity and rate of future climate impacts on ocean systems and ocean-reliant human communities will vary based on GHG trajectories, which are the outcomes of societal choices (KMs 2.3, 3.1). Local, regional, and sectoral impacts will be influenced by the pace and effectiveness of adaptation efforts.[10]

An increasing number of efforts indicate the potential for ocean-based mitigation and adaptation solutions. Advances in mitigation are being realized through the production of ocean-based renewable energy,[156,157] decarbonization of the maritime shipping industry (KM 13.2),[147] and expansion of aquatic food systems with lower overall emissions (KM 11.1).[177] In addition, nature-based solutions such as the preservation and restoration of blue carbon ecosystems (Focus on Blue Carbon)[220] and carbon dioxide removal techniques that leverage ocean systems and enhance the ocean's natural carbon sink (KM 32.3)[172] may offer cost-efficient and effective approaches that support carbon mitigation, climate adaptation, and biodiversity.[185,186,221] However, the benefits for adaptation and biodiversity are presently more clear than long-term benefits for mitigation (e.g., carbon sequestration), and more research would be needed to understand scales at which mitigation benefits are realized, rates of benefit growth over time, and the effectiveness of specific measures relative to other mitigation options.[187,222]

Even with swift and ambitious reductions in GHG emissions, climate impacts to oceans will continue.[179] Existing studies document how ocean users, economic sectors, and communities in the US are reacting to climate impacts with a variety of strategies, including business changes, early warning systems, evidence-based management, resilience planning, governance adjustments, and technological innovations.[10,69,96,122] Disparities are expected because not all individuals and communities are equally able to adapt, yet few studies exist to understand the types of disparities that are arising, how they are distributed among different communities and groups, and the extent to which they are mediated by factors such as social connectivity, wealth, or the diversity of available livelihood options.[4,86,182]

There is increasing evidence that adaptation strategies that are highly coordinated, planned in advance, and applied to larger scales lead to more durable, equitable outcomes.[7,10] Regardless of the adaptation approach, there is strong and abundant evidence that with continued increases in emissions, the number of effective adaptation options will decrease.[213] Plentiful and diverse evidence from the US and worldwide indicates that future conditions will make it more difficult to maintain ecological, social, cultural, and economic interconnections related to ocean ecosystems.[213]

### Major Uncertainties and Research Gaps

A greater understanding of the relative benefits and risks of adaptation strategies, conditions that influence effectiveness, feasibility of uptake by different groups of people, and implementation costs is needed. Limited data and research are available to quantify the socioeconomic impacts of climate change and how they vary among communities or groups or to evaluate how social conditions and interactions (e.g., economic, governance, or social coordination) influence choices, implementation, and effectiveness of adaptation options.[10] Limits to adaptation are not yet well known for ecosystems, individuals, and communities. Whether certain conditions, such as social connectivity, flexibility, socioeconomic assets, and

livelihood diversity,[4,182] insulate marine resource users from climate impacts and how they can be enhanced are still emerging areas of understanding.

How ocean-based mitigation solutions would affect marine ecosystems, existing uses of the ocean, and marine-dependent human communities is not yet well understood. The GHG-reduction potential and costs of many ocean-based mitigation options are still highly uncertain, and more information is needed to fully assess their effectiveness, scalability, and affordability.[169,176] There is an emerging body of information about how offshore wind development may affect the surrounding physical and natural system,[159] and some of these insights may apply to techniques under development, such as ocean carbon dioxide removal. Development of new ocean uses is expected to alter access for other activities, but it is unclear how adaptation strategies and mitigation measures may influence ocean use patterns and the types of users who may be advantaged or disadvantaged by these changes.[193]

The strong relationship between ambitious mitigation and a larger portfolio of effective adaptations is recognized across many ecosystems and sectors. However, data exist for only a limited number of ocean ecosystems, such as warm-water coral reefs and mangroves,[10] and additional ocean-focused studies would improve understanding. There is relatively little information on trade-offs among adaptation choices or interactions between ocean-focused adaptation, mitigation, and prevailing social conditions. These connections are mainly derived from analogy with coastal and terrestrial systems, where evidence about human–natural system decision-making tends to be more available.

## Description of Confidence and Likelihood

Across a range of studies, climate change impacts are affecting marine social–ecological systems, and risks are projected to increase in the future.[213] Projections consistently indicate that risks to marine social–ecological systems are lower under climate scenarios that achieve high mitigation and adaptation and that are implemented sooner, yielding *very high confidence* in this pattern of outcomes.[10] A broader array of adaptation options will be preserved if they are implemented sooner and keep pace with the rate of climate change impacts,[7,10] giving *very high confidence* that earlier adaptation will enhance outcomes and reduce costs. Impacts are being observed in communities that heavily depend on marine resources and have limited capacity to adapt, including Indigenous communities, resource-dependent economies, and smaller-scale fisheries.[58,68,86,118,163] These studies give *high confidence* that impacts are uneven and that intentional considerations that promote equitable mitigation and adaptation are required to reduce disproportionate impacts.

# References


1. BEA, 2023: Marine Economy Satellite Account, 2021: New Statistics for 2021; 2014–2020 Updated. BEA 23–24. U.S. Department of Commerce, Bureau of Economic Analysis. https://www.bea.gov/sites/default/files/2023-06/mesa0623.pdf

2. Pecl, G.T., M.B. Araújo, J.D. Bell, J. Blanchard, T.C. Bonebrake, I.-C. Chen, T.D. Clark, R.K. Colwell, F. Danielsen, B. Evengård, L. Falconi, S. Ferrier, S. Frusher, R.A. Garcia, R.B. Griffis, A.J. Hobday, C. Janion-Scheepers, M.A. Jarzyna, S. Jennings, J. Lenoir, H.I. Linnetved, V.Y. Martin, P.C. McCormack, J. McDonald, N.J. Mitchell, T. Mustonen, J.M. Pandolfi, N. Pettorelli, E. Popova, S.A. Robinson, B.R. Scheffers, J.D. Shaw, C.J.B. Sorte, J.M. Strugnell, J.M. Sunday, M.-N. Tuanmu, A. Vergés, C. Villanueva, T. Wernberg, E. Wapstra, and S.E. Williams, 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355** (6332), eaai9214. https://doi.org/10.1126/science.aai9214

3. Tigchelaar, M., W.W.L. Cheung, E.Y. Mohammed, M.J. Phillips, H.J. Payne, E.R. Selig, C.C.C. Wabnitz, M.A. Oyinlola, T.L. Frölicher, J.A. Gephart, C.D. Golden, E.H. Allison, A. Bennett, L. Cao, J. Fanzo, B.S. Halpern, V.W.Y. Lam, F. Micheli, R.L. Naylor, U.R. Sumaila, A. Tagliabue, and M. Troell, 2021: Compound climate risks threaten aquatic food system benefits. *Nature Food*, **2** (9), 673–682. https://doi.org/10.1038/s43016-021-00368-9

4. Colburn, L.L., M. Jepson, C. Weng, T. Seara, J. Weiss, and J.A. Hare, 2016: Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. *Marine Policy*, **74**, 323–333. https://doi.org/10.1016/j.marpol.2016.04.030

5. Crosman, K.M., E.H. Allison, Y. Ota, A.M. Cisneros-Montemayor, G.G. Singh, W. Swartz, M. Bailey, K.M. Barclay, G. Blume, M. Colléter, M. Fabinyi, E.M. Faustman, R. Fielding, P.J. Griffin, Q. Hanich, H. Harden-Davies, R.P. Kelly, T.-A. Kenny, T. Klinger, J.N. Kittinger, K. Nakamura, A.P. Pauwelussen, S. Pictou, C. Rothschild, K.L. Seto, and A.K. Spalding, 2022: Social equity is key to sustainable ocean governance. *npj Ocean Sustainability*, **1** (1), 4. https://doi.org/10.1038/s44183-022-00001-7

6. Mason, J.G., J.G. Eurich, J.D. Lau, W. Battista, C.M. Free, K.E. Mills, K. Tokunaga, L.Z. Zhao, M. Dickey-Collas, M. Valle, G.T. Pecl, J.E. Cinner, T.R. McClanahan, E.H. Allison, W.R. Friedman, C. Silva, E. Yáñez, M.Á. Barbieri, and K.M. Kleisner, 2022: Attributes of climate resilience in fisheries: From theory to practice. *Fish and Fisheries*, **23** (3), 522–544. https://doi.org/10.1111/faf.12630

7. Hicke, J.A., S. Lucatello, L.D. Mortsch, J. Dawson, M.D. Aguilar, C.A.F. Enquist, E.A. Gilmore, D.S. Gutzler, S. Harper, K. Holsman, E.B. Jewett, T.A. Kohler, and K. Miller, 2022: Ch. 14. North America. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1929–2042. https://doi.org/10.1017/9781009325844.016

8. Schipper, E.L.F., A. Revi, B.L. Preston, E.R. Carr, S.H. Eriksen, L.R. Fernandez-Carril, B.C. Glavovic, N.J.M. Hilmi, D. Ley, R. Mukerji, M.S.M.d. Araujo, R. Perez, S.K. Rose, and P.K. Singh, 2022: Ch. 18. Climate resilient development pathways. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2655–2807. https://doi.org/10.1017/9781009325844.027

9. Trebilco, R., A. Fleming, A.J. Hobday, J. Melbourne-Thomas, A. Meyer, J. McDonald, P.C. McCormack, K. Anderson, N. Bax, S.P. Corney, L.X.C. Dutra, H.E. Fogarty, J. McGee, K. Mustonen, T. Mustonen, K.A. Norris, E. Ogier, A.J. Constable, and G.T. Pecl, 2022: Warming world, changing ocean: Mitigation and adaptation to support resilient marine systems. *Reviews in Fish Biology and Fisheries*, **32** (1), 39–63. https://doi.org/10.1007/s11160-021-09678-4

10. Cooley, S., D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehiwet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, and M. Skern-Mauritzen, 2022: Ch. 3. Oceans and coastal ecosystems and their services. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 379–550. https://doi.org/10.1017/9781009325844.005

11. Bennett, N.J., A.M. Cisneros-Montemayor, J. Blythe, J.J. Silver, G. Singh, N. Andrews, A. Calò, P. Christie, A. Di Franco, E.M. Finkbeiner, S. Gelcich, P. Guidetti, S. Harper, N. Hotte, J.N. Kittinger, P. Le Billon, J. Lister, R. López de la Lama, E. McKinley, J. Scholtens, A.-M. Solås, M. Sowman, N. Talloni-Álvarez, L.C.L. Teh, M. Voyer, and U.R. Sumaila, 2019: Towards a sustainable and equitable blue economy. *Nature Sustainability*, **2** (11), 991–993. https://doi.org/10.1038/s41893-019-0404-1

12. Gruber, N., P.W. Boyd, T.L. Frölicher, and M. Vogt, 2021: Biogeochemical extremes and compound events in the ocean. *Nature*, **600** (7889), 395–407. https://doi.org/10.1038/s41586-021-03981-7

13. IPCC, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964

14. Trainer, V.L., S.K. Moore, G. Hallegraeff, R.M. Kudela, A. Clement, J.I. Mardones, and W.P. Cochlan, 2020: Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful Algae*, **91**, 101591. https://doi.org/10.1016/j.hal.2019.03.009

15. Free, C.M., J.T. Thorson, M.L. Pinsky, K.L. Oken, J. Wiedenmann, and O.P. Jensen, 2019: Impacts of historical warming on marine fisheries production. *Science*, **363** (6430), 979–983. https://doi.org/10.1126/science.aau1758

16. Langan, J.A., G. Puggioni, C.A. Oviatt, M.E. Henderson, and J.S. Collie, 2021: Climate alters the migration phenology of coastal marine species. *Marine Ecology Progress Series*, **660**, 1–18. https://doi.org/10.3354/meps13612

17. Pinsky, M.L., B. Worm, M.J. Fogarty, J.L. Sarmiento, and S.A. Levin, 2013: Marine taxa track local climate velocities. *Science*, **341** (6151), 1239–1242. https://doi.org/10.1126/science.1239352

18. Staudinger, M.D., K.E. Mills, K. Stamieszkin, N.R. Record, C.A. Hudak, A. Allyn, A. Diamond, K.D. Friedland, W. Golet, M.E. Henderson, C.M. Hernandez, T.G. Huntington, R. Ji, C.L. Johnson, D.S. Johnson, A. Jordaan, J. Kocik, Y. Li, M. Liebman, O.C. Nichols, D. Pendleton, R.A. Richards, T. Robben, A.C. Thomas, H.J. Walsh, and K. Yakola, 2019: It's about time: A synthesis of changing phenology in the Gulf of Maine ecosystem. *Fisheries Oceanography*, **28** (5), 532–566. https://doi.org/10.1111/fog.12429

19. Tableau, A., J.S. Collie, R.J. Bell, and C. Minto, 2019: Decadal changes in the productivity of New England fish populations. *Canadian Journal of Fisheries and Aquatic Sciences*, **76** (9), 1528–1540. https://doi.org/10.1139/cjfas-2018-0255

20. Beas-Luna, R., F. Micheli, C.B. Woodson, M. Carr, D. Malone, J. Torre, C. Boch, J.E. Caselle, M. Edwards, J. Freiwald, S.L. Hamilton, A. Hernandez, B. Konar, K.J. Kroeker, J. Lorda, G. Montaño-Moctezuma, and G. Torres-Moye, 2020: Geographic variation in responses of kelp forest communities of the California Current to recent climatic changes. *Global Change Biology*, **26** (11), 6457–6473. https://doi.org/10.1111/gcb.15273

21. Farr, E.R., M.R. Johnson, M.W. Nelson, J.A. Hare, W.E. Morrison, M.D. Lettrich, B. Vogt, C. Meaney, U.A. Howson, P.J. Auster, F.A. Borsuk, D.C. Brady, M.J. Cashman, P. Colarusso, J.H. Grabowski, J.P. Hawkes, R. Mercaldo-Allen, D.B. Packer, and D.K. Stevenson, 2021: An assessment of marine, estuarine, and riverine habitat vulnerability to climate change in the Northeast U.S. *PLoS ONE*, **16** (12), e0260654. https://doi.org/10.1371/journal.pone.0260654

22. Hughes, T.P., M.L. Barnes, D.R. Bellwood, J.E. Cinner, G.S. Cumming, J.B.C. Jackson, J. Kleypas, I.A. van de Leemput, J.M. Lough, T.H. Morrison, S.R. Palumbi, E.H. van Nes, and M. Scheffer, 2017: Coral reefs in the Anthropocene. *Nature*, **546**, 82–90. https://doi.org/10.1038/nature22901

23. Smale, D.A., 2020: Impacts of ocean warming on kelp forest ecosystems. *New Phytologist*, **225** (4), 1447–1454. https://doi.org/10.1111/nph.16107

24. Tonina, D., J.A. McKean, D. Isaak, R.M. Benjankar, C. Tang, and Q. Chen, 2022: Climate change shrinks and fragments salmon habitats in a snow-dependent region. *Geophysical Research Letters*, **49** (12), e2022GL098552. https://doi.org/10.1029/2022gl098552

25. Lenoir, J., R. Bertrand, L. Comte, L. Bourgeaud, T. Hattab, J. Murienne, and G. Grenouillet, 2020: Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, **4** (8), 1044–1059. https://doi.org/10.1038/s41559-020-1198-2

26. Laurel, B.J., M.E. Hunsicker, L. Ciannelli, T.P. Hurst, J. Duffy-Anderson, R. O'Malley, and M. Behrenfeld, 2021: Regional warming exacerbates match/mismatch vulnerability for cod larvae in Alaska. *Progress in Oceanography*, **193**, 102555. https://doi.org/10.1016/j.pocean.2021.102555

27. Thorne, L.H. and J.A. Nye, 2021: Trait-mediated shifts and climate velocity decouple an endothermic marine predator and its ectothermic prey. *Scientific Reports*, **11** (1), 18507. https://doi.org/10.1038/s41598-021-97318-z

28. McMahan, M.D., G.D. Sherwood, and J.H. Grabowski, 2020: Geographic variation in life-history traits of black sea bass (*Centropristis striata*) during a rapid range expansion. *Frontiers in Marine Science*, **7**, 567758. https://doi.org/10.3389/fmars.2020.567758

29. Kress, S.W., P. Shannon, C. O'Neal, and S. Cooke, 2017: Recent changes in the diet and survival of Atlantic puffin chicks in the face of climate change and commercial fishing in midcoast Maine, USA. *FACETS*, **1**, 27–43. https://doi.org/10.1139/facets-2015-0009

30. Piatt, J.F., J.K. Parrish, H.M. Renner, S.K. Schoen, T.T. Jones, M.L. Arimitsu, K.J. Kuletz, B. Bodenstein, M. García-Reyes, R.S. Duerr, R.M. Corcoran, R.S.A. Kaler, G.J. McChesney, R.T. Golightly, H.A. Coletti, R.M. Suryan, H.K. Burgess, J. Lindsey, K. Lindquist, P.M. Warzybok, J. Jahncke, J. Roletto, and W.J. Sydeman, 2020: Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014–2016. *PLoS ONE*, **15** (1), e0226087. https://doi.org/10.1371/journal.pone.0226087

31. Scopel, L., A. Diamond, S. Kress, and P. Shannon, 2019: Varied breeding responses of seabirds to a regime shift in prey base in the Gulf of Maine. *Marine Ecology Progress Series*, **626**, 177–196. https://doi.org/10.3354/meps13048

32. Le Bris, A., K.E. Mills, R.A. Wahle, Y. Chen, M.A. Alexander, A.J. Allyn, J.G. Schuetz, J.D. Scott, and A.J. Pershing, 2018: Climate vulnerability and resilience in the most valuable North American fishery. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (8), 1831–1836. https://doi.org/10.1073/pnas.1711122115

33. Hare, J.A., W.E. Morrison, M.W. Nelson, M.M. Stachura, E.J. Teeters, R.B. Griffis, M.A. Alexander, J.D. Scott, L. Alade, R.J. Bell, A.S. Chute, K.L. Curti, T.H. Curtis, D. Kircheis, J.F. Kocik, S.M. Lucey, C.T. McCandless, L.M. Milke, D.E. Richardson, E. Robillard, H.J. Walsh, M.C. McManus, K.E. Marancik, and C.A. Griswold, 2016: A vulnerability assessment of fish and invertebrates to climate change on the northeast U.S. continental shelf. *PLoS ONE*, **11** (2), e0146756. https://doi.org/10.1371/journal.pone.0146756

34. McClure, M.M., M.A. Haltuch, E. Willis-Norton, D.D. Huff, E.L. Hazen, L.G. Crozier, M.G. Jacox, M.W. Nelson, K.S. Andrews, L.A.K. Barnett, A.M. Berger, S. Beyer, J. Bizzarro, D. Boughton, J.M. Cope, M. Carr, H. Dewar, E. Dick, E. Dorval, J. Dunham, V. Gertseva, C.M. Greene, R.G. Gustafson, O.S. Hamel, C.J. Harvey, M.J. Henderson, C.E. Jordan, I.C. Kaplan, S.T. Lindley, N.J. Mantua, S.E. Matson, M.H. Monk, P. Moyle, C. Nicol, J. Pohl, R.R. Rykaczewski, J.F. Samhouri, S. Sogard, N. Tolimieri, J. Wallace, C. Wetzel, and S.J. Bograd, 2023: Vulnerability to climate change of managed stocks in the California Current Large Marine Ecosystem. *Frontiers in Marine Science*, **10**, 1103767. https://doi.org/10.3389/fmars.2023.1103767

35. Raymond, W.W., J.S. Barber, M.N. Dethier, H.A. Hayford, C.D.G. Harley, T.L. King, B. Paul, C.A. Speck, E.D. Tobin, A.E.T. Raymond, and P.S. McDonald, 2022: Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. *Ecology*, **103** (10), e3798. https://doi.org/10.1002/ecy.3798

36. Crozier, L.G., M.M. McClure, T. Beechie, S.J. Bograd, D.A. Boughton, M. Carr, T.D. Cooney, J.B. Dunham, C.M. Greene, M.A. Haltuch, E.L. Hazen, D.M. Holzer, D.D. Huff, R.C. Johnson, C.E. Jordan, I.C. Kaplan, S.T. Lindley, N.J. Mantua, P.B. Moyle, J.M. Myers, M.W. Nelson, B.C. Spence, L.A. Weitkamp, T.H. Williams, and E. Willis-Norton, 2019: Climate vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. *PLoS ONE*, **14** (7), e0217711. https://doi.org/10.1371/journal.pone.0217711

37. Meyer-Gutbrod, E.L., C.H. Greene, K.T.A. Davies, and D.G. Johns, 2021: Ocean regime shift is driving collapse of the North Atlantic right whale population. *Oceanography*, **34** (3), 22–31. https://doi.org/10.5670/oceanog.2021.308

38. Mills, K.E., A.J. Pershing, T.F. Sheehan, and D. Mountain, 2013: Climate and ecosystem linkages explain widespread declines in North American Atlantic salmon populations. *Global Change Biology*, **19** (10), 3046–3061. https://doi.org/10.1111/gcb.12298

39. Trombetta, T., F. Vidussi, C. Roques, M. Scotti, and B. Mostajir, 2020: Marine microbial food web networks during phytoplankton bloom and non-bloom periods: Warming favors smaller organism interactions and intensifies trophic cascade. *Frontiers in Microbiology*, **11**, 502336. https://doi.org/10.3389/fmicb.2020.502336

40. Carlson, C.J., S. Hopkins, K.C. Bell, J. Doña, S.S. Godfrey, M.L. Kwak, K.D. Lafferty, M.L. Moir, K.A. Speer, G. Strona, M. Torchin, and C.L. Wood, 2020: A global parasite conservation plan. *Biological Conservation*, **250**, 108596. https://doi.org/10.1016/j.biocon.2020.108596

41. Wood, C.L., R.L. Welicky, W.C. Preisser, K.L. Leslie, N. Mastick, C. Greene, K.P. Maslenikov, L. Tornabene, J.M. Kinsella, and T.E. Essington, 2023: A reconstruction of parasite burden reveals one century of climate-associated parasite decline. *Proceedings of the National Academy of Sciences of the United States of America*, **120** (3), e2211903120. https://doi.org/10.1073/pnas.2211903120

42. Ward, E.J., J.H. Anderson, T.J. Beechie, G.R. Pess, and M.J. Ford, 2015: Increasing hydrologic variability threatens depleted anadromous fish populations. *Global Change Biology*, **21** (7), 2500–2509. https://doi.org/10.1111/gcb.12847

43. Wang, H., Q. Chen, M.K. La Peyre, K. Hu, and J.F. La Peyre, 2017: Predicting the impacts of Mississippi River diversions and sea-level rise on spatial patterns of eastern oyster growth rate and production. *Ecological Modelling*, **352**, 40–53. https://doi.org/10.1016/j.ecolmodel.2017.02.028

44. Macreadie, P.I., M.D.P. Costa, T.B. Atwood, D.A. Friess, J.J. Kelleway, H. Kennedy, C.E. Lovelock, O. Serrano, and C.M. Duarte, 2021: Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, **2** (12), 826–839. https://doi.org/10.1038/s43017-021-00224-1

45. Prouty, N.G., A. Cohen, K.K. Yates, C.D. Storlazzi, P.W. Swarzenski, and D. White, 2017: Vulnerability of coral reefs to bioerosion from land-based source of pollution. *Journal of Geophysical Research Oceans*, **122** (12), 9319–9331. https://doi.org/10.1002/2017jc013264

46. Armstrong, C.W., G.K. Vondolia, N.S. Foley, L.-A. Henry, K. Needham, and A. Ressurreição, 2019: Expert assessment of risks posed by climate change and anthropogenic activities to ecosystem services in the deep North Atlantic. *Frontiers in Marine Science*, **6**, 158. https://doi.org/10.3389/fmars.2019.00158

47. Prouty, N.G., E.B. Roark, A.E. Koenig, A.W.J. Demopoulos, F.C. Batista, B.D. Kocar, D. Selby, M.D. McCarthy, F. Mienis, and S.W. Ross, 2014: Deep-sea coral record of human impact on watershed quality in the Mississippi River Basin. *Global Biogeochemical Cycles*, **28** (1), 29–43. https://doi.org/10.1002/2013GB004754

48. Levin, L.A., 2021: IPCC and the deep sea: A case for deeper knowledge. *Frontiers in Climate*, **3**, 720755. https://doi.org/10.3389/fclim.2021.720755

49. Levin, L.A. and N. Le Bris, 2015: The deep ocean under climate change. *Science*, **350** (6262), 766–768. https://doi.org/10.1126/science.aad0126

50. Sweetman, A.K., A.R. Thurber, C.R. Smith, L.A. Levin, C. Mora, C.-L. Wei, A.J. Gooday, D.O.B. Jones, M. Rex, M. Yasuhara, J. Ingels, H.A. Ruhl, C.A. Frieder, R. Danovaro, L. Würzberg, A. Baco, B.M. Grupe, A. Pasulka, K.S. Meyer, K.M. Dunlop, L.-A. Henry, and J.M. Roberts, 2017: Major impacts of climate change on deep-sea benthic ecosystems. *Elementa: Science of the Anthropocene*, **5**, 4. https://doi.org/10.1525/elementa.203

51. Hilmi, N., R. Chami, M.D. Sutherland, J.M. Hall-Spencer, L. Lebleu, M.B. Benitez, and L.A. Levin, 2021: The role of blue carbon in climate change mitigation and carbon stock conservation. *Frontiers in Climate*, **3**, 710546. https://doi.org/10.3389/fclim.2021.710546

52. Burge, C.A., C.M. Eakin, C.S. Friedman, B. Froelich, P.K. Hershberger, E.E. Hofmann, L.E. Petes, K.C. Prager, E. Weil, B.L. Willis, S.E. Ford, and C.D. Harvell, 2014: Climate change influences on marine infectious diseases: Implications for management and society. *Annual Review of Marine Science*, **6** (1), 249–277. https://doi.org/10.1146/annurev-marine-010213-135029

53. Heil, C.A. and A.L. Muni-Morgan, 2021: Florida's harmful algal bloom (HAB) problem: Escalating risks to human, environmental and economic health with climate change. *Frontiers in Ecology and Evolution*, **9**, 646080. https://doi.org/10.3389/fevo.2021.646080

54. Huntington, H.P., A. Zagorsky, B.P. Kaltenborn, H.C. Shin, J. Dawson, M. Lukin, P.E. Dahl, P. Guo, and D.N. Thomas, 2022: Societal implications of a changing Arctic Ocean. *Ambio*, **51** (2), 298–306. https://doi.org/10.1007/s13280-021-01601-2

55. Ritzman, J., A. Brodbeck, S. Brostrom, S. McGrew, S. Dreyer, T. Klinger, and S.K. Moore, 2018: Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 U.S. West Coast harmful algal bloom. *Harmful Algae*, **80**, 35–45. https://doi.org/10.1016/j.hal.2018.09.002

56. Green, K.M., J.C. Selgrath, T.H. Frawley, W.K. Oestreich, E.J. Mansfield, J. Urteaga, S.S. Swanson, F.N. Santana, S.J. Green, J. Naggea, and L.B. Crowder, 2021: How adaptive capacity shapes the Adapt, React, Cope response to climate impacts: Insights from small-scale fisheries. *Climatic Change*, **164** (1), 15. https://doi.org/10.1007/s10584-021-02965-w

57. Hauser, D.D.W., A.V. Whiting, A.R. Mahoney, J. Goodwin, C. Harris, R.J. Schaeffer, R. Schaeffer, N.J.M. Laxague, A. Subramaniam, C.R. Witte, S. Betcher, J.M. Lindsay, and C.J. Zappa, 2021: Co-production of knowledge reveals loss of Indigenous hunting opportunities in the face of accelerating Arctic climate change. *Environmental Research Letters*, **16** (9), 095003. https://doi.org/10.1088/1748-9326/ac1a36

58. Huntington, H.P., S.L. Danielson, F.K. Wiese, M. Baker, P. Boveng, J.J. Citta, A. De Robertis, D.M.S. Dickson, E. Farley, J.C. George, K. Iken, D.G. Kimmel, K. Kuletz, C. Ladd, R. Levine, L. Quakenbush, P. Stabeno, K.M. Stafford, D. Stockwell, and C. Wilson, 2020: Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, **10** (4), 342–348. https://doi.org/10.1038/s41558-020-0695-2

59. Lefebvre, K.A., E. Fachon, E.K. Bowers, D.G. Kimmel, J.A. Snyder, R. Stimmelmayr, J.M. Grebmeier, S. Kibler, D. Ransom Hardison, D.M. Anderson, D. Kulis, J. Murphy, J.C. Gann, D. Cooper, L.B. Eisner, J.T. Duffy-Anderson, G. Sheffield, R.S. Pickart, A. Mounsey, M.L. Willis, P. Stabeno, and E. Siddon, 2022: Paralytic shellfish toxins in Alaskan Arctic food webs during the anomalously warm ocean conditions of 2019 and estimated toxin doses to Pacific walruses and bowhead whales. *Harmful Algae*, **114**, 102205. https://doi.org/10.1016/j.hal.2022.102205

60. Lefebvre, K.A., L. Quakenbush, E. Frame, K. Burek, G. Sheffield, R. Stimmelmayr, A. Bryan, P. Kendrick, H. Ziel, T. Goldstein, J.A. Snyder, T. Gelatt, F. Gulland, B. Dickerson, and V. Gill, 2016: Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. *Harmful Algae*, **55**, 13–24. https://doi.org/10.1016/j.hal.2016.01.007

61. McCabe, R.M., B.M. Hickey, R.M. Kudela, K.A. Lefebvre, N.G. Adams, B.D. Bill, F.M.D. Gulland, R.E. Thomson, W.P. Cochlan, and V.L. Trainer, 2016: An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, **43** (19), 10366–10376. https://doi.org/10.1002/2016gl070023

62. Scaggs, S.A., D. Gerkey, and K.R. McLaughlin, 2021: Linking subsistence harvest diversity and productivity to adaptive capacity in an Alaskan food sharing network. *American Journal of Human Biology*, **33** (4), e23573. https://doi.org/10.1002/ajhb.23573

63. Huntington, H.P., L.T. Quakenbush, and M. Nelson, 2017: Evaluating the effects of climate change on indigenous marine mammal hunting in northern and western Alaska using traditional knowledge. *Frontiers in Marine Science*, **4**, 319. https://doi.org/10.3389/fmars.2017.00319

64. Scyphers, S.B., J.S. Picou, and J.H. Grabowski, 2019: Chronic social disruption following a systemic fishery failure. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (46), 22912–22914. https://doi.org/10.1073/pnas.1913914116

65. Slats, R., C. Oliver, R. Bahnke, H. Bell, A. Miller, D. Pungowiyi, J. Merculief, N. Menadelook Sr., J. Ivanoff, and C. Oxereok, 2019: Voices from the Front Lines of a Changing Bering Sea: An Indigenous Perspective for the 2019 Arctic Report Card. NOAA Arctic Report Card, Druckenmiller, M.L., R. Daniel, and M. Johnson, Eds. National Oceanic and Atmospheric Administration, Arctic Research Program, 88–99 pp. https://arctic.noaa.gov/report-card/report-card-2019/voices-from-the-front-lines-of-a-changing-bering-sea/

66. Tremblay, R., M. Landry-Cuerrier, and M.M. Humphries, 2020: Culture and the social-ecology of local food use by Indigenous communities in northern North America. *Ecology and Society*, **25** (2), 8. https://doi.org/10.5751/es-11542-250208

67. Jacox, M.G., M.A. Alexander, S.J. Bograd, and J.D. Scott, 2020: Thermal displacement by marine heatwaves. *Nature*, **584** (7819), 82–86. https://doi.org/10.1038/s41586-020-2534-z

68. Huntington, H.P., J. Raymond-Yakoubian, G. Noongwook, N. Naylor, C. Harris, Q. Harcharek, and B. Adams, 2021: "We never get stuck:" A collaborative analysis of change and coastal community subsistence practices in the Northern Bering and Chukchi Seas, Alaska. *Arctic*, **74** (2), 113–126. https://doi.org/10.14430/arctic72446

69. Pershing, A., K. Mills, A. Dayton, B. Franklin, and B. Kennedy, 2018: Evidence for adaptation from the 2016 marine heatwave in the Northwest Atlantic Ocean. *Oceanography*, **31** (2), 152–161. https://doi.org/10.5670/oceanog.2018.213

70. Samhouri, J.F., B.E. Feist, M.C. Fisher, O. Liu, S.M. Woodman, B. Abrahms, K.A. Forney, E.L. Hazen, D. Lawson, J. Redfern, and L.E. Saez, 2021: Marine heatwave challenges solutions to human-wildlife conflict. *Proceedings of the Royal Society B: Biological Sciences*, **288** (1964), 20211607. https://doi.org/10.1098/rspb.2021.1607

71. Bograd, S.J., M.G. Jacox, E.L. Hazen, E. Lovecchio, I. Montes, M. Pozo Buil, L.J. Shannon, W.J. Sydeman, and R.R. Rykaczewski, 2023: Climate change impacts on eastern boundary upwelling systems. *Annual Review of Marine Science*, **15** (1), 303–328. https://doi.org/10.1146/annurev-marine-032122-021945

72. Hodapp, D., I.T. Roca, D. Fiorentino, C. Garilao, K. Kaschner, K. Kesner-Reyes, B. Schneider, J. Segschneider, Á.T. Kocsis, W. Kiessling, T. Brey, and R. Froese, 2023: Climate change disrupts core habitats of marine species. *Global Change Biology*, **29** (12), 3304–3317. https://doi.org/10.1111/gcb.16612

73. Sheahan, M., C.A. Gould, J.E. Neumann, P.L. Kinney, S. Hoffmann, C. Fant, X. Wang, and M. Kolian, 2022: Examining the relationship between climate change and vibriosis in the United States: Projected health and economic impacts for the 21st century. *Environmental Health Perspectives*, **130** (8), 087007. https://doi.org/10.1289/ehp9999a

74. Tester, P.A., R.W. Litaker, and E. Berdalet, 2020: Climate change and harmful benthic microalgae. *Harmful Algae*, **91**, 101655. https://doi.org/10.1016/j.hal.2019.101655

75. Tittensor, D.P., C. Novaglio, C.S. Harrison, R.F. Heneghan, N. Barrier, D. Bianchi, L. Bopp, A. Bryndum-Buchholz, G.L. Britten, M. Büchner, W.W.L. Cheung, V. Christensen, M. Coll, J.P. Dunne, T.D. Eddy, J.D. Everett, J.A. Fernandes-Salvador, E.A. Fulton, E.D. Galbraith, D. Gascuel, J. Guiet, J.G. John, J.S. Link, H.K. Lotze, O. Maury, K. Ortega-Cisneros, J. Palacios-Abrantes, C.M. Petrik, H. du Pontavice, J. Rault, A.J. Richardson, L. Shannon, Y.-J. Shin, J. Steenbeek, C.A. Stock, and J.L. Blanchard, 2021: Next-generation ensemble projections reveal higher climate risks for marine ecosystems. *Nature Climate Change*, **11** (11), 973–981. https://doi.org/10.1038/s41558-021-01173-9

76. Heinze, C., T. Blenckner, H. Martins, D. Rusiecka, R. Döscher, M. Gehlen, N. Gruber, E. Holland, Ø. Hov, F. Joos, J.B.R. Matthews, R. Rødven, and S. Wilson, 2021: The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (9), e2008478118. https://doi.org/10.1073/pnas.2008478118

77. Hoegh-Guldberg, O., L. Pendleton, and A. Kaup, 2019: People and the changing nature of coral reefs. *Regional Studies in Marine Science*, **30**, 100699. https://doi.org/10.1016/j.rsma.2019.100699

78. Penn, J.L. and C. Deutsch, 2022: Avoiding ocean mass extinction from climate warming. *Science*, **376** (6592), 524–526. https://doi.org/10.1126/science.abe9039

79. Stewart-Sinclair, P.J., K.S. Last, B.L. Payne, and T.A. Wilding, 2020: A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. *Ecology and Evolution*, **10** (7), 3518–3534. https://doi.org/10.1002/ece3.6149

80. Dubik, B.A., E.C. Clark, T. Young, S.B.J. Zigler, M.M. Provost, M.L. Pinsky, and K. St. Martin, 2019: Governing fisheries in the face of change: Social responses to long-term geographic shifts in a U.S. fishery. *Marine Policy*, **99**, 243–251. https://doi.org/10.1016/j.marpol.2018.10.032

81. Cucuzza, M.L., H.L. Sagar, and R.B. Griffis, 2021: Synthesis of Public Comments to NOAA on Executive Order 14008, Tackling the Climate Crisis at Home and Abroad, Section 216(c): Recommendations on How to Make Fisheries and Protected Resources, Including Aquaculture, More Resilient to Climate Change. NOAA Technical Memorandum NMFS-F/SPO-218. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 79 pp. https://spo.nmfs.noaa.gov/content/tech-memo/synthesis-public-comments-noaa-executive-order-14008-tackling-climate-crisis-home

82. Jacox, M.G., M.A. Alexander, N.J. Mantua, J.D. Scott, G. Hervieux, R.S. Webb, and F.E. Werner, 2018: Forcing of multiyear extreme ocean temperatures that impacted California Current living marine resources in 2016. *Bulletin of the American Meteorological Society*, **99** (1), S27–S33. https://doi.org/10.1175/bams-d-17-0119.1

83. Santora, J.A., N.J. Mantua, I.D. Schroeder, J.C. Field, E.L. Hazen, S.J. Bograd, W.J. Sydeman, B.K. Wells, J. Calambokidis, L. Saez, D. Lawson, and K.A. Forney, 2020: Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications*, **11** (1), 536. https://doi.org/10.1038/s41467-019-14215-w

84. Ryan, J.P., R.M. Kudela, J.M. Birch, M. Blum, H.A. Bowers, F.P. Chavez, G.J. Doucette, K. Hayashi, R. Marin III, C.M. Mikulski, J.T. Pennington, C.A. Scholin, G.J. Smith, A. Woods, and Y. Zhang, 2017: Causality of an extreme harmful algal bloom in Monterey Bay, California, during the 2014–2016 northeast Pacific warm anomaly. *Geophysical Research Letters*, **44** (11), 5571–5579. https://doi.org/10.1002/2017gl072637

85. Fisher, M.C., S.K. Moore, S.L. Jardine, J.R. Watson, and J.F. Samhouri, 2021: Climate shock effects and mediation in fisheries. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2014379117. https://doi.org/10.1073/pnas.2014379117

86. Jardine, S.L., M.C. Fisher, S.K. Moore, and J.F. Samhouri, 2020: Inequality in the economic impacts from climate shocks in fisheries: The case of harmful algal blooms. *Ecological Economics*, **176**, 106691. https://doi.org/10.1016/j.ecolecon.2020.106691

87. Smith, J.A., M. Pozo Buil, J. Fiechter, D. Tommasi, and M.G. Jacox, 2022: Projected novelty in the climate envelope of the California Current at multiple spatial-temporal scales. *PLoS Climate*, **1** (4), e0000022. https://doi.org/10.1371/journal.pclm.0000022

88. Pershing, A.J., N.R. Record, B.S. Franklin, B.T. Kennedy, L. McClenachan, K.E. Mills, J.D. Scott, A.C. Thomas, and N.H. Wolff, 2019: Challenges to natural and human communities from surprising ocean temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (37), 18378–18383. https://doi.org/10.1073/pnas.1901084116

89. OCM, 2022: Digital Coasts. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. https://coast.noaa.gov/digitalcoast/

90. Cheung, W.W.L. and T.L. Frölicher, 2020: Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. *Scientific Reports*, **10** (1), 6678. https://doi.org/10.1038/s41598-020-63650-z

91. Smale, D.A., T. Wernberg, E.C.J. Oliver, M. Thomsen, B.P. Harvey, S.C. Straub, M.T. Burrows, L.V. Alexander, J.A. Benthuysen, M.G. Donat, M. Feng, A.J. Hobday, N.J. Holbrook, S.E. Perkins-Kirkpatrick, H.A. Scannell, A. Sen Gupta, B.L. Payne, and P.J. Moore, 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9** (4), 306–312. https://doi.org/10.1038/s41558-019-0412-1

92. Lam, V.W.Y., W.W.L. Cheung, G. Reygondeau, and U.R. Sumaila, 2016: Projected change in global fisheries revenues under climate change. *Scientific Reports*, **6** (1), 1–8. https://doi.org/10.1038/srep32607

93. Sumaila, U.R., T.C. Tai, V.W.Y. Lam, W.W.L. Cheung, M. Bailey, A.M. Cisneros-Montemayor, O.L. Chen, and S.S. Gulati, 2019: Benefits of the Paris Agreement to ocean life, economies, and people. *Science Advances*, **5** (2), 3855. https://doi.org/10.1126/sciadv.aau3855

94. Bhattachan, A., M.D. Jurjonas, A.C. Moody, P.R. Morris, G.M. Sanchez, L.S. Smart, P.J. Taillie, R.E. Emanuel, and E.L. Seekamp, 2018: Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making. *Environmental Science & Policy*, **90**, 122–134. https://doi.org/10.1016/j.envsci.2018.10.006

95. Jurjonas, M. and E. Seekamp, 2018: Rural coastal community resilience: Assessing a framework in eastern North Carolina. *Ocean & Coastal Management*, **162**, 137–150. https://doi.org/10.1016/j.ocecoaman.2017.10.010

96. Bell, R.J., J. Odell, G. Kirchner, and S. Lomonico, 2020: Actions to promote and achieve climate-ready fisheries: Summary of current practice. *Marine and Coastal Fisheries*, **12** (3), 166–190. https://doi.org/10.1002/mcf2.10112

97. Watson, J.T. and A.C. Haynie, 2018: Paths to resilience: The walleye pollock fleet uses multiple fishing strategies to buffer against environmental change in the Bering Sea. *Canadian Journal of Fisheries and Aquatic Sciences*, **75** (11), 1977–1989. https://doi.org/10.1139/cjfas-2017-0315

98. Fedewa, E.J., T.M. Jackson, J.I. Richar, J.L. Gardner, and M.A. Litzow, 2020: Recent shifts in northern Bering Sea snow crab (*Chionoecetes opilio*) size structure and the potential role of climate-mediated range contraction. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181–182**, 104878. https://doi.org/10.1016/j.dsr2.2020.104878

99. Jones, M.C., M. Berkelhammer, K.J. Keller, K. Yoshimura, and M.J. Wooller, 2020: High sensitivity of Bering Sea winter sea ice to winter insolation and carbon dioxide over the last 5500 years. *Science Advances*, **6** (36). https://doi.org/10.1126/sciadv.aaz9588

100. Spies, I., K.M. Gruenthal, D.P. Drinan, A.B. Hollowed, D.E. Stevenson, C.M. Tarpey, and L. Hauser, 2020: Genetic evidence of a northward range expansion in the eastern Bering Sea stock of Pacific cod. *Evolutionary Applications*, **13** (2), 362–375. https://doi.org/10.1111/eva.12874

101. Stevenson, D.E. and R.R. Lauth, 2019: Bottom trawl surveys in the northern Bering Sea indicate recent shifts in the distribution of marine species. *Polar Biology*, **42** (2), 407–421. https://doi.org/10.1007/s00300-018-2431-1

102. Szuwalski, C., 2022: An Assessment for Eastern Bering Sea Snow Crab. North Pacific Fishery Management Council, Anchorage, AK. https://meetings.npfmc.org/commentreview/downloadfile?p=fca55335-ad34-4896-9b1e-4c09aa8342ce.pdf&filename=ebs%20snow%20safe%20final.pdf

103. Whitmore, K., A. Richards, J. Carloni, M. Hunter, M. Hawk, and K. Drew, 2013: Assessment Report for Gulf of Maine Northern Shrimp—2013. Atlantic States Marine Fisheries Commission, Arlington, VA, 86 pp. http://www.asmfc.org/species/northern-shrimp

104. Bellquist, L., V. Saccomanno, B.X. Semmens, M. Gleason, and J. Wilson, 2021: The rise in climate change-induced federal fishery disasters in the United States. *PeerJ*, **9**, e11186. https://doi.org/10.7717/peerj.11186

105. Barbeaux, S.J., K. Holsman, and S. Zador, 2020: Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific cod fishery. *Frontiers in Marine Science*, **7**, 703. https://doi.org/10.3389/fmars.2020.00703

106. Pershing, A.J., M.A. Alexander, C.M. Hernandez, L.A. Kerr, A. Le Bris, K.E. Mills, J.A. Nye, N.R. Record, H.A. Scannell, J.D. Scott, G.D. Sherwood, and A.C. Thomas, 2015: Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science*, **350** (6262), 809–812. https://doi.org/10.1126/science.aac9819

107. Chasco, B.E., M.E. Hunsicker, K.C. Jacobson, O.T. Welch, C.A. Morgan, B.A. Muhling, and J.A. Harding, 2022: Evidence of temperature-driven shifts in market squid *Doryteuthis opalescens* densities and distribution in the California Current ecosystem. *Marine and Coastal Fisheries*, **14** (1), e10190. https://doi.org/10.1002/mcf2.10190

108. Goethel, D.R., D.H. Hanselman, C.J. Rodgveller, K.H. Fenske, S.K. Shotwell, K.B. Echave, P.W. Malecha, K.A. Siwicke, and C.R. Lunsford, 2020: Assessment of the Sablefish Stock in Alaska. NPFMC Bering Sea, Aleutian Islands and Gulf of Alaska SAFE. https://apps-afsc.fisheries.noaa.gov/refm/docs/2020/sablefish.pdf

109. Hollowed, A.B., K.K. Holsman, A.C. Haynie, A.J. Hermann, A.E. Punt, K. Aydin, J.N. Ianelli, S. Kasperski, W. Cheng, A. Faig, K.A. Kearney, J.C.P. Reum, P. Spencer, I. Spies, W. Stockhausen, C.S. Szuwalski, G.A. Whitehouse, and T.K. Wilderbuer, 2020: Integrated modeling to evaluate climate change impacts on coupled social-ecological systems in Alaska. *Frontiers in Marine Science*, **6**, 775. https://doi.org/10.3389/fmars.2019.00775

110. Holsman, K.K., A.C. Haynie, A.B. Hollowed, J.C.P. Reum, K. Aydin, A.J. Hermann, W. Cheng, A. Faig, J.N. Ianelli, K.A. Kearney, and A.E. Punt, 2020: Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications*, **11** (1), 4579. https://doi.org/10.1038/s41467-020-18300-3

111. Rheuban, J.E., M.T. Kavanaugh, and S.C. Doney, 2017: Implications of future northwest Atlantic bottom temperatures on the American lobster (*Homarus americanus*) fishery. *Journal of Geophysical Research: Oceans*, **122** (12), 9387–9398. https://doi.org/10.1002/2017jc012949

112. Szuwalski, C., W. Cheng, R. Foy, A.J. Hermann, A. Hollowed, K. Holsman, J. Lee, W. Stockhausen, and J. Zheng, 2021: Climate change and the future productivity and distribution of crab in the Bering Sea. *ICES Journal of Marine Science*, **78** (2), 502–515. https://doi.org/10.1093/icesjms/fsaa140

113. Moore, C., J.W. Morley, B. Morrison, M. Kolian, E. Horsch, T. Frölicher, M.L. Pinsky, and R. Griffis, 2021: Estimating the economic impacts of climate change on 16 major US fisheries. *Climate Change Economics*, **12** (1), 2150002. https://doi.org/10.1142/s2010007821500020

114. Hanich, Q., C.C.C. Wabnitz, Y. Ota, M. Amos, C. Donato-Hunt, and A. Hunt, 2018: Small-scale fisheries under climate change in the Pacific Islands region. *Marine Policy*, **88**, 279–284. https://doi.org/10.1016/j.marpol.2017.11.011

115. Ojea, E., I. Pearlman, S.D. Gaines, and S.E. Lester, 2017: Fisheries regulatory regimes and resilience to climate change. *Ambio*, **46** (4), 399–412. https://doi.org/10.1007/s13280-016-0850-1

116. Palacios-Abrantes, J., T.L. Frölicher, G. Reygondeau, U.R. Sumaila, A. Tagliabue, Colette C.C. Wabnitz, and William W.L. Cheung, 2022: Timing and magnitude of climate-driven range shifts in transboundary fish stocks challenge their management. *Global Change Biology*, **28** (7), 2312–2326. https://doi.org/10.1111/gcb.16058

117. Pinsky, M.L., G. Reygondeau, R. Caddell, J. Palacios-Abrantes, J. Spijkers, and W.W.L. Cheung, 2018: Preparing ocean governance for species on the move. *Science*, **360** (6394), 1189–1191. https://doi.org/10.1126/science.aat2360

118. Young, T., E.C. Fuller, M.M. Provost, K.E. Coleman, K. St. Martin, B.J. McCay, and M.L. Pinsky, 2019: Adaptation strategies of coastal fishing communities as species shift poleward. *ICES Journal of Marine Science*, **76** (1), 93–103. https://doi.org/10.1093/icesjms/fsy140

119. Sainsbury, N.C., M.J. Genner, G.R. Saville, J.K. Pinnegar, C.K. O'Neill, S.D. Simpson, and R.A. Turner, 2018: Changing storminess and global capture fisheries. *Nature Climate Change*, **8** (8), 655–659. https://doi.org/10.1038/s41558-018-0206-x

120. NMFS, 2021: U.S. Seafood Industry and For-Hire Sector Impacts from COVID-19: 2020 in Perspective. NOAA Technical Memorandum NMFS-SPO-221. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 88 pp. https://spo.nmfs.noaa.gov/sites/default/files/TM221.pdf

121. Cline, T.J., D.E. Schindler, and R. Hilborn, 2017: Fisheries portfolio diversification and turnover buffer Alaskan fishing communities from abrupt resource and market changes. *Nature Communications*, **8** (1), 14042. https://doi.org/10.1038/ncomms14042

122. Holsman, K.K., E.L. Hazen, A. Haynie, S. Gourguet, A. Hollowed, S.J. Bograd, J.F. Samhouri, and K. Aydin, 2019: Towards climate resiliency in fisheries management. *ICES Journal of Marine Science*, **76** (5), 1368–1378. https://doi.org/10.1093/icesjms/fsz031

123. Woods, P.J., J.I. Macdonald, H. Bárðarson, S. Bonanomi, W.J. Boonstra, G. Cornell, G. Cripps, R. Danielsen, L. Färber, A.S.A. Ferreira, K. Ferguson, M. Holma, R.E. Holt, K.L. Hunter, A. Kokkalis, T.J. Langbehn, G. Ljungström, E. Nieminen, M.C. Nordström, M. Oostdijk, A. Richter, G. Romagnoni, C. Sguotti, A. Simons, N.L. Shackell, M. Snickars, J.D. Whittington, H. Wootton, and J. Yletyinen, 2022: A review of adaptation options in fisheries management to support resilience and transition under socio-ecological change. *ICES Journal of Marine Science*, **79** (2), 463–479. https://doi.org/10.1093/icesjms/fsab146

124. Stoll, J.S., C.M. Beitl, and J.A. Wilson, 2016: How access to Maine's fisheries has changed over a quarter century: The cumulative effects of licensing on resilience. *Global Environmental Change*, **37**, 79–91. https://doi.org/10.1016/j.gloenvcha.2016.01.005

125. Catch Together, 2020: Pacific Coast Fisheries Diversification Framework. The Nature Conservancy, 77 pp. https://www.nature.org/content/dam/tnc/nature/en/documents/Port_Orford_Framework_Document_Final.pdf

126. Stoll, J.S., B.A. Dubik, and L.M. Campbell, 2015: Local seafood: Rethinking the direct marketing paradigm. *Ecology and Society*, **20** (2), 40. https://doi.org/10.5751/es-07686-200240

127. Hazen, E.L., K.L. Scales, S.M. Maxwell, D.K. Briscoe, H. Welch, S.J. Bograd, H. Bailey, S.R. Benson, T. Eguchi, H. Dewar, S. Kohin, D.P. Costa, L.B. Crowder, and R.L. Lewison, 2018: A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances*, **4** (5), 3001. https://doi.org/10.1126/sciadv.aar3001

128. Collie, J.S., R.J. Bell, S.B. Collie, and C. Minto, 2021: Harvest strategies for climate-resilient fisheries. *ICES Journal of Marine Science*, **78** (8), 2774–2783. https://doi.org/10.1093/icesjms/fsab152

129. Northrop, E., P. Schuhmann, L. Burke, A. Fyall, S. Alvarez, A. Spenceley, S. Becken, K. Kato, J. Roy, S. Some, J. Veitayaki, A. Markandya, I. Galarraga, P. Greño, I. Ruiz-Gauna, M. Curnock, M.E. Wood, M.Y. Yin, S. Riedmiller, E. Carter, R. Haryanto, E. Holloway, R. Croes, J. Ridderstaat, and M. Godovykh, 2022: Opportunities for Transforming Coastal and Marine Tourism: Towards Sustainability, Regeneration and Resilience. World Resources Institute, Washington, DC. https://oceanpanel.org/publication/opportunities-for-transforming-coastal-and-marine-tourism-towards-sustainability-regeneration-and-resilience/

130. Reineman, D.R., L.N. Thomas, and M.R. Caldwell, 2017: Using local knowledge to project sea level rise impacts on wave resources in California. *Ocean & Coastal Management*, **138**, 181–191. https://doi.org/10.1016/j.ocecoaman.2017.01.020

131. Hallegraeff, G.M., D.M. Anderson, C. Belin, M.-Y.D. Bottein, E. Bresnan, M. Chinain, H. Enevoldsen, M. Iwataki, B. Karlson, C.H. McKenzie, I. Sunesen, G.C. Pitcher, P. Provoost, A. Richardson, L. Schweibold, P.A. Tester, V.L. Trainer, A.T. Yñiguez, and A. Zingone, 2021: Perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts. *Communications Earth & Environment*, **2** (1), 117. https://doi.org/10.1038/s43247-021-00178-8

132. Wang, M., C. Hu, B.B. Barnes, G. Mitchum, B. Lapointe, and J.P. Montoya, 2019: The great Atlantic *Sargassum* belt. *Science*, **365** (6448), 83–87. https://doi.org/10.1126/science.aaw7912

133. Bechard, A., 2020: Harmful algal blooms and tourism: The economic impact to counties in southwest Florida. *Review of Regional Studies*, **50** (2), 170–188. https://doi.org/10.52324/001c.12705

134. Burrowes, R., C. Wabnitz, and J. Eyzaguirre, 2019: The Great Sargassum Disaster of 2018. ESSA Technologies. https://www.essa.com/the-great-sargassum-disaster-of-2018/

135. Townhill, B.L., Z. Radford, G. Pecl, I. van Putten, J.K. Pinnegar, and K. Hyder, 2019: Marine recreational fishing and the implications of climate change. *Fish and Fisheries*, **20** (5), 977–992. https://doi.org/10.1111/faf.12392

136. Dundas, S.J. and R.H. von Haefen, 2020: The effects of weather on recreational fishing demand and adaptation: Implications for a changing climate. *Journal of the Association of Environmental and Resource Economists*, **7** (2), 209–242. https://doi.org/10.1086/706343

137. Palma, D., A. Varnajot, K. Dalen, I.K. Basaran, C. Brunette, M. Bystrowska, A.D. Korablina, R.C. Nowicki, and T.A. Ronge, 2019: Cruising the marginal ice zone: Climate change and Arctic tourism. *Polar Geography*, **42** (4), 215–235. https://doi.org/10.1080/1088937x.2019.1648585

138. Spalding, M., L. Burke, S.A. Wood, J. Ashpole, J. Hutchison, and P. zu Ermgassen, 2017: Mapping the global value and distribution of coral reef tourism. *Marine Policy*, **82**, 104–113. https://doi.org/10.1016/j.marpol.2017.05.014

139. Van Deren, M., J. Mojica, J. Martin, C. Armistead, and C. Koefod, 2019: The Whales in Our Waters: The Economic Benefits of Whale Watching in San Juan County. Earth Economics, Tacoma, WA. https://www.eartheconomics.org/srkw

140. Dawson, J., L. Pizzolato, S.E.L. Howell, L. Copland, and M.E. Johnston, 2018: Temporal and spatial patterns of ship traffic in the Canadian Arctic from 1990 to 2015. *Journal of The Arctic Institute of North America*, **71** (1). https://doi.org/10.14430/arctic4698

141. Li, X., S.R. Stephenson, A.H. Lynch, M.A. Goldstein, D.A. Bailey, and S. Veland, 2021: Arctic shipping guidance from the CMIP6 ensemble on operational and infrastructural timescales. *Climatic Change*, **167** (1), 23. https://doi.org/10.1007/s10584-021-03172-3

142. CRS, 2023: Changes in the Arctic: Background and Issues for Congress. CRS Report R41153. Congressional Research Service. https://crsreports.congress.gov/product/pdf/r/r41153

143. Mudryk, L.R., J. Dawson, S.E.L. Howell, C. Derksen, T.A. Zagon, and M. Brady, 2021: Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. *Nature Climate Change*, **11** (8), 673–679. https://doi.org/10.1038/s41558-021-01087-6

144. Arrigo, K.R., G.L. van Dijken, M.A. Cameron, J. van der Grient, L.M. Wedding, L. Hazen, J. Leape, G. Leonard, A. Merkl, F. Micheli, M.M. Mills, S. Monismith, N.T. Ouellette, A. Zivian, M. Levi, and R.M. Bailey, 2020: Synergistic interactions among growing stressors increase risk to an Arctic ecosystem. *Nature Communications*, **11** (1), 6255. https://doi.org/10.1038/s41467-020-19899-z

145. Ivanova, S.V., S.T. Kessel, M. Espinoza, M.F. McLean, C. O'Neill, J. Landry, N.E. Hussey, R. Williams, S. Vagle, and A.T. Fisk, 2020: Shipping alters the movement and behavior of Arctic cod (*Boreogadus saida*), a keystone fish in Arctic marine ecosystems. *Ecological Applications*, **30** (3), e02050. https://doi.org/10.1002/eap.2050

146. Zhang, Q., Z. Wan, B. Hemmings, and F. Abbasov, 2019: Reducing black carbon emissions from Arctic shipping: Solutions and policy implications. *Journal of Cleaner Production*, **241**, 118261. https://doi.org/10.1016/j.jclepro.2019.118261

147. IMO, 2020: Fourth Greenhouse Gas Study 2020. International Maritime Organization, London, UK. https://www.imo.org/en/ourwork/environment/pages/fourth-imo-greenhouse-gas-study-2020.aspx

148. EPA, 2023: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021. EPA 430-R-23-002. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021

149. Daniel, H., J.P.F. Trovão, and D. Williams, 2022: Shore power as a first step toward shipping decarbonization and related policy impact on a dry bulk cargo carrier. *eTransportation*, **11**, 100150. https://doi.org/10.1016/j.etran.2021.100150

150. GOV.UK, 2022: COP 26: Clydebank Declaration for Green Shipping Corridors. HM Government, Department for Transport. https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration-for-green-shipping-corridors

151. Nichols, W. and R. Clisby, 2021: 40% of Oil and Gas Reserves Threatened by Climate Change. Verisk Maplecroft. https://www.maplecroft.com/insights/analysis/40-of-oil-and-gas-reserves-threatened-by-climate-change/

152. Burkett, V., 2011: Global climate change implications for coastal and offshore oil and gas development. *Energy Policy*, **39** (12), 7719–7725. https://doi.org/10.1016/j.enpol.2011.09.016

153. Casas-Prat, M. and X.L. Wang, 2020: Projections of extreme ocean waves in the Arctic and potential implications for coastal inundation and erosion. *Journal of Geophysical Research: Oceans*, **125** (8), e2019JC015745. https://doi.org/10.1029/2019jc015745

154. Dong, J., Z. Asif, Y. Shi, Y. Zhu, and Z. Chen, 2022: Climate change impacts on coastal and offshore petroleum infrastructure and the associated oil spill risk: A review. *Journal of Marine Science and Engineering*, **10** (7), 849. https://doi.org/10.3390/jmse10070849

155. Ebad Sichani, M., K.A. Anarde, K.M. Capshaw, J.E. Padgett, R.A. Meidl, P. Hassanzadeh, T.P. Loch-Temzelides, and P.B. Bedient, 2020: Hurricane risk assessment of petroleum infrastructure in a changing climate. *Frontiers in Built Environment*, **6**, 104. https://doi.org/10.3389/fbuil.2020.00104

156. The White House, 2021: Fact sheet: Biden administration jumpstarts offshore wind energy projects to create jobs. The White House, Washington, DC, March 29, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/

157. BOEM, 2022: Outer Continental Shelf Renewable Energy Leases: Map Book. OREP-2022-2006. U.S. Department of the Interior, Bureau of Ocean Energy Management. https://www.boem.gov/sites/default/files/documents/renewable-energy/Leases-Map-Book-July%202022.pdf

158. Christopher, T.R., M. Goldstein, M. Williams, and A. Carter, 2022: The Road to 30 Gigawatts: Key Actions to Scale an Offshore Wind Industry in the United States. Center for American Progress. https://www.americanprogress.org/article/the-road-to-30-gigawatts-key-actions-to-scale-an-offshore-wind-industry-in-the-united-states/

159. Hogan, F., B. Hooker, B. Jensen, L. Johnston, A. Lipsky, E. Methratta, A. Silva, and A. Hawkins, 2023: Fisheries and Offshore Wind Interactions: Synthesis of Science. NOAA Technical Memorandum NMFS-NE-291. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center, Woods Hole, MA. https://doi.org/10.25923/tcjt-3a69

160. Klain, S.C., T. Satterfield, S. MacDonald, N. Battista, and K.M.A. Chan, 2017: Will communities "open-up" to offshore wind? Lessons learned from New England islands in the United States. *Energy Research & Social Science*, **34**, 13–26. https://doi.org/10.1016/j.erss.2017.05.009

161. Methratta, E.T., A. Hawkins, B.R. Hooker, A. Lipsky, and J.A. Hare, 2020: Offshore wind development in the Northeast US Shelf Large Marine Ecosystem: Ecological, human, and fishery management dimensions. *Oceanography*, **33** (4), 16–27. https://doi.org/10.5670/oceanog.2020.402

162. Tyler, G., D. Bidwell, T. Smythe, and S. Trandafir, 2022: Preferences for community benefits for offshore wind development projects: A case study of the Outer Banks of North Carolina, U.S. *Journal of Environmental Policy & Planning*, **24** (1), 39–55. https://doi.org/10.1080/1523908x.2021.1940896

163. Koehn, L.E., L.K. Nelson, J.F. Samhouri, K.C. Norman, M.G. Jacox, A.C. Cullen, J. Fiechter, M. Pozo Buil, and P.S. Levin, 2022: Social-ecological vulnerability of fishing communities to climate change: A U.S. West Coast case study. *PLoS ONE*, **17** (8), e0272120. https://doi.org/10.1371/journal.pone.0272120

164. MAFMC, 2022: East Coast Climate Change Scenario Planning. Mid-Atlantic Fishery Management Council. https://www.mafmc.org/climate-change-scenario-planning

165. PFMC, 2022: Climate and Communities Initiative. Pacific Fishery Management Council. https://www.pcouncil.org/actions/climate-and-communities-initiative/

166. Cities of Portland and South Portland, 2021: One Climate Future: Charting a Course for Portland and South Portland. Portland and South Portland Sustainability Offices. https://www.oneclimatefuture.org/wp-content/uploads/2021/02/OneClimateFuture_FinalJan2021_Downsized.pdf

167. Takak, L., H. Shepherd, G. Griffith, and M. Hall, 2021: Norton Bay Watershed Ocean and Coastal Management Plan (NBWOCMP): Protecting the Watershed's Subsistence Culture and Resources. Norton Bay Inter-Tribal Watershed Council. https://www.nortonbaywatershed.org/wp-content/uploads/2022/01/Norton-Bay-Watershed-Ocean-and-Coastal-Management-Plan-NBWOCMP_8-25-21_FNLv3-merged.pdf

168. Gattuso, J.-P., A.K. Magnan, L. Bopp, W.W.L. Cheung, C.M. Duarte, J. Hinkel, E. Mcleod, F. Micheli, A. Oschlies, P. Williamson, R. Billé, V.I. Chalastani, R.D. Gates, J.-O. Irisson, J.J. Middelburg, H.-O. Pörtner, and G.H. Rau, 2018: Ocean solutions to address climate change and its effects on marine ecosystems. *Frontiers in Marine Science*, **5**, 337. https://doi.org/10.3389/fmars.2018.00337

169. Williamson, P. and J.-P. Gattuso, 2022: Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. *Frontiers in Climate*, **4**, 853666. https://doi.org/10.3389/fclim.2022.853666

170. ARPA-E, 2022: Direct Removal of Carbon Dioxide from Oceanwater. U.S. Department of Energy, Advanced Research Projects Agency–Energy, accessed May 26, 2022. https://arpa-e.energy.gov/technologies/exploratory-topics/direct-ocean-capture

171. Bertram, C. and C. Merk, 2020: Public perceptions of ocean-based carbon dioxide removal: The nature-engineering divide? *Frontiers in Climate*, **2**, 594194. https://doi.org/10.3389/fclim.2020.594194

172. National Academies of Sciences, Engineering, and Medicine, 2022: *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*. The National Academies Press, Washington, DC, 322 pp. https://doi.org/10.17226/26278

173. Silverman-Roati, K., M.B. Gerrard, and R.M. Webb, 2021: Removing Carbon Dioxide Through Seaweed Cultivation: Legal Challenges and Opportunities. Columbia Law School, Sabin Center for Climate Change Law. https://scholarship.law.columbia.edu/faculty_scholarship/2980

174. XPRIZE, 2022: $100M Prize for Carbon Removal. XPRIZE Foundation, accessed May 26, 2022. https://www.xprize.org/prizes/elonmusk

175. University of Hawai'i, 2021: $6M for UH wave energy conversion research. *University of Hawaiʻi News*, August 11, 2021. https://www.hawaii.edu/news/2021/08/11/wave-energy-conversion-6m/

176. Hoegh-Guldberg, O., K. Caldeira, T. Chopin, S. Gaines, P. Haugan, M. Hemer, J. Howard, M. Konar, D. Krause-Jensen, E. Lindstad, C. Lovelock, M. Michelin, F. Nielsen, E. Northrop, R. Parker, J. Roy, T. Smith, S. Some, and P. Tyedmers, 2019: The Ocean as a Solution to Climate Change: Five Opportunities for Action. World Resources Institute, Washington, DC. https://oceanpanel.org/publication/the-ocean-as-a-solution-to-climate-change-five-opportunities-for-action/

177. Gephart, J.A., P.J.G. Henriksson, R.W.R. Parker, A. Shepon, K.D. Gorospe, K. Bergman, G. Eshel, C.D. Golden, B.S. Halpern, S. Hornborg, M. Jonell, M. Metian, K. Mifflin, R. Newton, P. Tyedmers, W. Zhang, F. Ziegler, and M. Troell, 2021: Environmental performance of blue foods. *Nature*, **597** (7876), 360–365. https://doi.org/10.1038/s41586-021-03889-2

178. UNEP, 2021: Emissions Gap Report 2021: The Heat Is On–A World of Climate Promises Not Yet Delivered. United Nations Environment Programme, Nairobi, Kenya. https://www.unep.org/emissions-gap-report-2021

179. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

180. Ellam Yua, J. Raymond-Yakoubian, R. Aluaq Daniel, and C. Behe, 2022: A framework for co-production of knowledge in the context of Arctic research. *Ecology and Society*, **27** (1), 34. https://doi.org/10.5751/es-12960-270134

181. Huntington, H.P., M. Carey, C. Apok, B.C. Forbes, S. Fox, L.K. Holm, A. Ivanova, J. Jaypoody, G. Noongwook, and F. Stammler, 2019: Climate change in context: Putting people first in the Arctic. *Regional Environmental Change*, **19** (4), 1217–1223. https://doi.org/10.1007/s10113-019-01478-8

182. Degroot, D., K. Anchukaitis, M. Bauch, J. Burnham, F. Carnegy, J. Cui, K. de Luna, P. Guzowski, G. Hambrecht, H. Huhtamaa, A. Izdebski, K. Kleemann, E. Moesswilde, N. Neupane, T. Newfield, Q. Pei, E. Xoplaki, and N. Zappia, 2021: Towards a rigorous understanding of societal responses to climate change. *Nature*, **591** (7851), 539–550. https://doi.org/10.1038/s41586-021-03190-2

183. Boström-Einarsson, L., R.C. Babcock, E. Bayraktarov, D. Ceccarelli, N. Cook, S.C.A. Ferse, B. Hancock, P. Harrison, M. Hein, E. Shaver, A. Smith, D. Suggett, P.J. Stewart-Sinclair, T. Vardi, and I.M. McLeod, 2020: Coral restoration–A systematic review of current methods, successes, failures and future directions. *PLoS ONE*, **15** (1), e0226631. https://doi.org/10.1371/journal.pone.0226631

184. Condie, S.A., K.R.N. Anthony, R.C. Babcock, M.E. Baird, R. Beeden, C.S. Fletcher, R. Gorton, D. Harrison, A.J. Hobday, É.E. Plagányi, and D.A. Westcott, 2021: Large-scale interventions may delay decline of the Great Barrier Reef. *Royal Society Open Science*, **8** (4), 201296. https://doi.org/10.1098/rsos.201296

185. Reguero, B.G., M.W. Beck, D.N. Bresch, J. Calil, and I. Meliane, 2018: Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLoS ONE*, **13** (4), e0192132. https://doi.org/10.1371/journal.pone.0192132

186. Riisager-Simonsen, C., G. Fabi, L. van Hoof, N. Holmgren, G. Marino, and D. Lisbjerg, 2022: Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans. *Marine Policy*, **144**, 105198. https://doi.org/10.1016/j.marpol.2022.105198

187. Seddon, N., A. Chausson, P. Berry, C.A.J. Girardin, A. Smith, and B. Turner, 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

188. Bremer, L.L., B. Keeler, P. Pascua, R. Walker, and E. Sterling, 2021: Ch. 5. Nature-based solutions, sustainable development, and equity. In: *Nature-Based Solutions and Water Security*. Cassin, J., J.H. Matthews, and E.L. Gunn, Eds. Elsevier, 81–105. https://doi.org/10.1016/b978-0-12-819871-1.00016-6

189. Water Power Technologies Office, 2022: 2020–2021 Accomplishments Report. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Water Power Technologies Office. https://www.energy.gov/sites/default/files/2022-03/wpto-accomplishments-report-march-2022.pdf

190. Taylor, J., J.-M. Bonello, D. Baresic, and T. Smith, 2022: Future Maritime Fuels in the USA—The Options and Their Potential Pathways. UMAS, London, UK, 59 pp. https://oceanconservancy.org/wp-content/uploads/2022/04/oc_fuels_final_report_20220117.pdf

191. Cooley, S.R., S. Klinsky, D.R. Morrow, and T. Satterfield, 2023: Sociotechnical considerations about ocean carbon dioxide removal. *Annual Review of Marine Science*, **15** (1), 41–66. https://doi.org/10.1146/annurev-marine-032122-113850

192. Mooney, T.A., M.H. Andersson, and J. Stanley, 2020: Acoustic impacts of offshore wind energy on fishery resources: An evolving source and varied effects across a wind farm's lifetime. *Oceanography*, **33** (4), 82–95. https://doi.org/10.5670/oceanog.2020.408

193. Perry, R. and W. Heyman, 2020: Considerations for offshore wind energy development effects on fish and fisheries in the United States: A review of existing studies, new efforts, and opportunities for innovation. *Oceanography*, **33** (4), 28–37. https://doi.org/10.5670/oceanog.2020.403

194. Gardiner, S.M., 2006: A Perfect Moral Storm: Climate change, intergenerational ethics and the problem of moral corruption. *Environmental Values*, **15** (3), 397–413. https://doi.org/10.3197/096327106778226293

195. Haas, B., M. Mackay, C. Novaglio, L. Fullbrook, M. Murunga, C. Sbrocchi, J. McDonald, P.C. McCormack, K. Alexander, M. Fudge, L. Goldsworthy, F. Boschetti, I. Dutton, L. Dutra, J. McGee, Y. Rousseau, E. Spain, R. Stephenson, J. Vince, C. Wilcox, and M. Haward, 2022: The future of ocean governance. *Reviews in Fish Biology and Fisheries*, **32** (1), 253–270. https://doi.org/10.1007/s11160-020-09631-x

196. Brett, A., J. Leape, M. Abbott, H. Sakaguchi, L. Cao, K. Chand, Y. Golbuu, T.J. Martin, J. Mayorga, and M.S. Myksvoll, 2020: Ocean data need a sea change to help navigate the warming world. *Nature*, **582** (7811), 181–183. https://doi.org/10.1038/d41586-020-01668-z

197. Chavez, F.P., M. Min, K. Pitz, N. Truelove, J. Baker, D. LaScala-Grunewald, M. Blum, K. Walz, C. Nye, A. Djurhuus, R.J. Miller, K.D. Goodwin, F.E. Muller-Karger, H.A. Ruhl, and C.A. Scholin, 2021: Observing life in the sea using environmental DNA. *Oceanography*, **34** (2), 102–119. https://doi.org/10.5670/oceanog.2021.218

198. Roemmich, D., L. Talley, N. Zilberman, E. Osborne, K. Johnson, L. Barbero, H. Bittig, N. Briggs, A. Fassbender, G. Johnson, B. King, E. McDonagh, S. Purkey, S. Riser, T. Suga, Y. Takeshita, V. Thierry, and S. Wijffels, 2021: The technological, scientific, and sociological revolution of global subsurface ocean observing. *Oceanography*, **34** (4), 2–8. https://doi.org/10.5670/oceanog.2021.supplement.02-02

199. Schmidt, J.O., S.J. Bograd, H. Arrizabalaga, J.L. Azevedo, S.J. Barbeaux, J.A. Barth, T. Boyer, S. Brodie, J.J. Cárdenas, S. Cross, J.-N. Druon, A. Fransson, J. Hartog, E.L. Hazen, A. Hobday, M. Jacox, J. Karstensen, S. Kupschus, J. Lopez, L.A.S.-P. Madureira, J.E. Martinelli Filho, P. Miloslavich, C.P. Santos, K. Scales, S. Speich, M.B. Sullivan, A. Szoboszlai, D. Tommasi, D. Wallace, S. Zador, and P.A. Zawislak, 2019: Future ocean observations to connect climate, fisheries and marine ecosystems. *Frontiers in Marine Science*, **6**, 550. https://doi.org/10.3389/fmars.2019.00550

200. Berkes, F., J. Colding, and C. Folke, 2000: Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications*, **10** (5), 1251–1262. https://doi.org/10.2307/2641280

201. Lam, D.P.M., E. Hinz, D.J. Lang, M. Tengö, H. von Wehrden, and B. Martín-López, 2020: Indigenous and local knowledge in sustainability transformations research: A literature review. *Ecology and Society*, **25** (1), 3. https://doi.org/10.5751/es-11305-250103

202. Moltmann, T., J. Turton, H.-M. Zhang, G. Nolan, C. Gouldman, L. Griesbauer, Z. Willis, Á.M. Piniella, S. Barrell, E. Andersson, C. Gallage, E. Charpentier, M. Belbeoch, P. Poli, A. Rea, E.F. Burger, D.M. Legler, R. Lumpkin, C. Meinig, K. O'Brien, K. Saha, A. Sutton, D. Zhang, and Y. Zhang, 2019: A Global Ocean Observing System (GOOS), delivered through enhanced collaboration across regions, communities, and new technologies. *Frontiers in Marine Science*, **6**, 291. https://doi.org/10.3389/fmars.2019.00291

203. Colgan, C.S., P. King, and S. Jenkins, 2021: California Coastal Recreation: Beyond the Beach. Publications. 1. Middlebury Institute of International Studies at Monterey, Center for the Blue Economy. https://cbe.miis.edu/publications/1

204. ERG and Synapse Energy Economics, 2020: Volume 2. Cost of doing nothing analysis. In: *Assessing the Impacts Climate Change May Have on the State's Economy, Revenues, and Investment Decisions: Summary Report*. Eastern Research Group and Synapse Energy Economics, Augusta, ME, 9–13. https://www.maine.gov/future/sites/maine.gov.future/files/inline-files/ERG_MCC_AssessingImpactsClimateChangeMaine_Summary.pdf

205. Wall, T.U., E. McNie, and G.M. Garfin, 2017: Use-inspired science: Making science usable by and useful to decision makers. *Frontiers in Ecology and the Environment*, **15** (10), 551–559. https://doi.org/10.1002/fee.1735

206. Jacox, M.G., M.A. Alexander, D. Amaya, E. Becker, S.J. Bograd, S. Brodie, E.L. Hazen, M. Pozo Buil, and D. Tommasi, 2022: Global seasonal forecasts of marine heatwaves. *Nature*, **604** (7906), 486–490. https://doi.org/10.1038/s41586-022-04573-9

207. Jacox, M.G., M.A. Alexander, S. Siedlecki, K. Chen, Y.-O. Kwon, S. Brodie, I. Ortiz, D. Tommasi, M.J. Widlansky, D. Barrie, A. Capotondi, W. Cheng, E. Di Lorenzo, C. Edwards, J. Fiechter, P. Fratantoni, E.L. Hazen, A.J. Hermann, A. Kumar, A.J. Miller, D. Pirhalla, M. Pozo Buil, S. Ray, S.C. Sheridan, A. Subramanian, P. Thompson, L. Thorne, H. Annamalai, K. Aydin, S.J. Bograd, R.B. Griffis, K. Kearney, H. Kim, A. Mariotti, M. Merrifield, and R. Rykaczewski, 2020: Seasonal-to-interannual prediction of North American coastal marine ecosystems: Forecast methods, mechanisms of predictability, and priority developments. *Progress in Oceanography*, **183**, 102307. https://doi.org/10.1016/j.pocean.2020.102307

208. Liu, G., C.M. Eakin, M. Chen, A. Kumar, J.L. De La Cour, S.F. Heron, E.F. Geiger, W.J. Skirving, K.V. Tirak, and A.E. Strong, 2018: Predicting heat stress to inform reef management: NOAA Coral Reef Watch's 4-month coral bleaching outlook. *Frontiers in Marine Science*, **5**, 57. https://doi.org/10.3389/fmars.2018.00057

209. Mills, K.E., A.J. Pershing, and C.M. Hernández, 2017: Forecasting the seasonal timing of Maine's lobster fishery. *Frontiers in Marine Science*, **4**, 337. https://doi.org/10.3389/fmars.2017.00337

210. Tommasi, D., C.A. Stock, A.J. Hobday, R. Methot, I.C. Kaplan, J.P. Eveson, K. Holsman, T.J. Miller, S. Gaichas, M. Gehlen, A. Pershing, G.A. Vecchi, R. Msadek, T. Delworth, C.M. Eakin, M.A. Haltuch, R. Séférian, C.M. Spillman, J.R. Hartog, S. Siedlecki, J.F. Samhouri, B. Muhling, R.G. Asch, M.L. Pinsky, V.S. Saba, S.B. Kapnick, C.F. Gaitan, R.R. Rykaczewski, M.A. Alexander, Y. Xue, K.V. Pegion, P. Lynch, M.R. Payne, T. Kristiansen, P. Lehodey, and F.E. Werner, 2017: Managing living marine resources in a dynamic environment: The role of seasonal to decadal climate forecasts. *Progress in Oceanography*, **152**, 15–49. https://doi.org/10.1016/j.pocean.2016.12.011

211. Bell, R., A. Strawn, and G. Kirchner, 2021: Flexibility in the Pacific Fisheries Management Council's Fishery Management Plans: What is Flexible Fisheries Management? The Nature Conservancy, Portland, OR. https://pfmc.psmfc.org/CommentReview/DownloadFile?p=5fdeb210-d94e-44e0-9fc5-a2c79ef1f2c3.pdf&fileName=1.2_Climate%20and%20Communities%20Initiative%20Update_Flexibility%20White%20Paper_TNC.pdf

212. Drenkard, E.J., C. Stock, A.C. Ross, K.W. Dixon, A. Adcroft, M. Alexander, V. Balaji, S.J. Bograd, M. Butenschön, W. Cheng, E. Curchitser, E.D. Lorenzo, R. Dussin, A.C. Haynie, M. Harrison, A. Hermann, A. Hollowed, K. Holsman, J. Holt, M.G. Jacox, C.J. Jang, K.A. Kearney, B.A. Muhling, M.P. Buil, V. Saba, A.B. Sandø, D. Tommasi, and M. Wang, 2021: Next-generation regional ocean projections for living marine resource management in a changing climate. *ICES Journal of Marine Science*, **78** (6), 1969–1987. https://doi.org/10.1093/icesjms/fsab100

213. IPCC, 2022: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844

214. Daniel, R., 2019: Understanding our environment requires an indigenous worldview. *Eos*, **100**. https://doi.org/10.1029/2019eo137482

215. Pershing, A.J., R.B. Griffis, E.B. Jewett, C.T. Armstrong, J.F. Bruno, D.S. Busch, A.C. Haynie, S.A. Siedlecki, and D. Tommasi, 2018: Ch. 9. Oceans and marine resources. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 353–390. https://doi.org/10.7930/nca4.2018.ch9

216. Levin, L.A., B.J. Bett, A.R. Gates, P. Heimbach, B.M. Howe, F. Janssen, A. McCurdy, H.A. Ruhl, P. Snelgrove, K.I. Stocks, D. Bailey, S. Baumann-Pickering, C. Beaverson, M.C. Benfield, D.J. Booth, M. Carreiro-Silva, A. Colaço, M.C. Eblé, A.M. Fowler, K.M. Gjerde, D.O.B. Jones, K. Katsumata, D. Kelley, N. Le Bris, A.P. Leonardi, F. Lejzerowicz, P.I. Macreadie, D. McLean, F. Meitz, T. Morato, A. Netburn, J. Pawlowski, C.R. Smith, S. Sun, H. Uchida, M.F. Vardaro, R. Venkatesan, and R.A. Weller, 2019: Global Observing needs in the deep ocean. *Frontiers in Marine Science*, **6**, 241. https://doi.org/10.3389/fmars.2019.00241

217. Sumaila, U.R., J. Palacios-Abrantes, and W.W.L. Cheung, 2020: Climate change, shifting threat points, and the management of transboundary fish stocks. *Ecology and Society*, **25** (4), 40. https://doi.org/10.5751/es-11660-250440

218. Colgan, C.S., 2016: The economics of adaptation to climate change in coasts and oceans: Literature review, policy implications and research agenda. *Journal of Ocean and Coastal Economics*, **3** (2), 1. https://doi.org/10.15351/2373-8456.1067

219. Constable, A.J., S. Harper, J. Dawson, K. Holsman, T. Mustonen, D. Piepenburg, and B. Rost, 2022: Cross-Chapter paper 6: Polar regions. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2319–2368. https://doi.org/10.1017/9781009325844.023

220. Mcleod, E., G.L. Chmura, S. Bouillon, R. Salm, M. Björk, C.M. Duarte, C.E. Lovelock, W.H. Schlesinger, and B.R. Silliman, 2011: A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering $CO_2$. *Frontiers in Ecology and the Environment*, **9** (10), 552–560. https://doi.org/10.1890/110004

221. Sasmito, S.D., D. Murdiyarso, D.A. Friess, and S. Kurnianto, 2016: Can mangroves keep pace with contemporary sea level rise? A global data review. *Wetlands Ecology and Management*, **24** (2), 263–278. https://doi.org/10.1007/s11273-015-9466-7

222. Scarano, F.R., 2017: Ecosystem-based adaptation to climate change: Concept, scalability and a role for conservation science. *Perspectives in Ecology and Conservation*, **15** (2), 65–73. https://doi.org/10.1016/j.pecon.2017.05.003

Fifth National Climate Assessment: Chapter 11

# Agriculture, Food Systems, and Rural Communities

# Chapter 11. Agriculture, Food Systems, and Rural Communities

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# Introduction

A changing climate, characterized by more frequent and severe extremes events, such as heatwaves, droughts, and extreme rainfall (KM 2.2), will affect US agriculture, food systems (a topic not addressed in previous National Climate Assessments [NCAs]), and rural communities. Climate change has increased risk to agricultural production, for example, by disrupting growing zones, growing days, and seasonality, making adaptation necessary to increase resilience in an evolving landscape (KM 11.1). Climate change is projected to reduce the availability and affordability of nutritious food, with impacts being unevenly distributed across society (KM 11.2). Rural communities, which manage much of the Nation's land and natural resources, face unique challenges and opportunities due to climate change (KM 11.3).

Agriculture has always faced unpredictable weather, but a changing climate poses additional challenges. Examples highlighted in NCA5 include extreme precipitation events damaging crops, delaying planting and harvesting, and expanding pest ranges in the Northeast (KM 21.1); increased average and extreme temperatures adversely affecting farmworker health in the Southeast and Southwest (Figure 11.1; KM 22.3); reductions in corn yield due to both excessive water and extreme drought in the Midwest (KM 24.1); greater incidence of heat stress on livestock in the Southwest (KM 28.3); and collapse of major fisheries in Alaska (KM 29.3).

Disruptions to food systems and supply chains within them (see Focus on Risks to Supply Chains) are expected to increase with climate change (KM 19.1). These disruptions are projected to make some food items more expensive and less accessible, particularly for lower-income individuals and households, including those in rural settings. Food insecurity affected 10.2% (13.5 million) of US households in 2021.[1] Historical structural inequities have influenced the distribution of resources, participation, accessibility, benefits, and burdens within the food system (Figure 20.1), and climate change will exacerbate these inequities (Figure 18.2). For example, many food system workers are both food insecure and disproportionately exposed to the effects of climate change, intensifying the socioeconomic impacts of these intertwined inequities.[2]

Rural communities supply labor for agricultural production and other economic sectors and often serve as stewards of the Nation's soil and water resources, having unique knowledge of rural landscapes. Climate change increases existing risks in rural communities, some of which have limited resources and infrastructure to adapt (KM 22.3). Many risks are disproportionately greater in some Black, Indigenous, Latino, and lower-income communities, and among some small-scale, beginning, and underrepresented farmers (KMs 15.2, 16.2, 22.4, 26.4, 31.2).

In summary, climate change poses significant challenges to US agricultural production, food systems, and rural communities—from primary producers to supporting industries to consumers. Climate-smart practices based on agroecological approaches are needed to both mitigate greenhouse gas emissions and adapt to ongoing climatic changes. Significant mitigation can occur through reductions in nitrous oxide emissions using precision technologies that target the right amount, source, placement, and timing of nitrogen fertilizer applications; formulation of methane-reducing diets in ruminant livestock systems; and conservation management with no-till, cover cropping, and perennial crop rotations to store more soil carbon. Many of these same agroecological approaches will support adaptation to climate change by improving soil health, increasing biological diversity, and making more efficient use of fertilizers, feed, water, and energy. Agricultural production is a complex web of biophysical and socioeconomic features interacting with environmental conditions, some of which are stable and some that are becoming less reliable with climate change. Reliance on more agroecological approaches is expected to help stabilize agricultural production while preserving the integrity of natural resources that are vital to support continued agricultural production in the future (KM 32.2). Agroecological approaches seek to achieve beneficial agricultural outcomes while promoting ecosystem services and rural livelihoods (Box 11.1).

### Farmworker Exposure to Extreme Heat and Smoke

**Climate change increases farmworker exposure to extreme heat and wildfire smoke.**

**Figure 11.1.** Farmworkers, for example, shown here in Salinas, California, face compounding health risks from extreme heat, wildfire smoke, and COVID-19 (see Ch. 15; KM 28.4; Focus on Western Wildfires; Focus on COVID-19 and Climate Change). Photo credit: ChuckSchugPhotography/iStock via Getty Images.

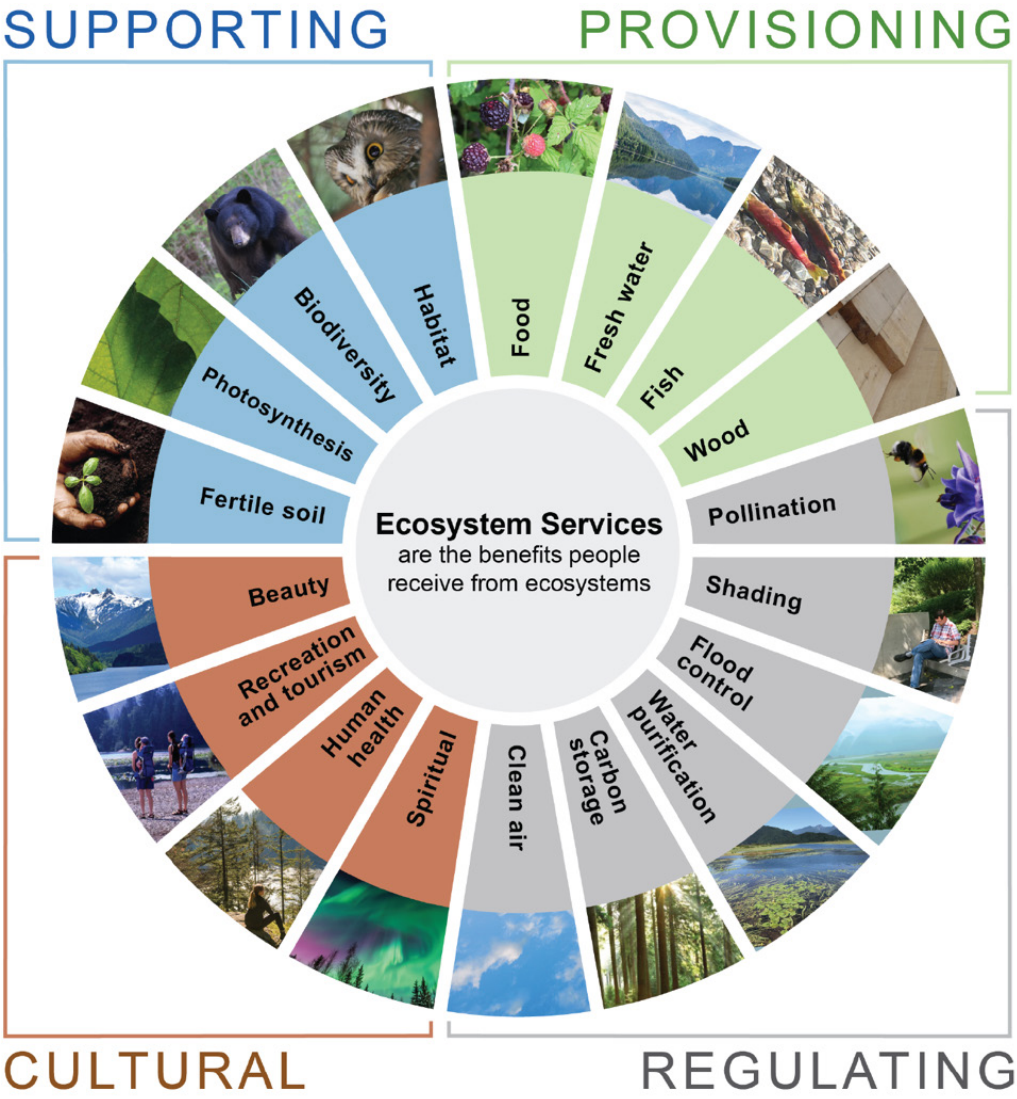
## Key Message 11.1

## Agricultural Adaptation Increases Resilience in an Evolving Landscape

Climate change has increased agricultural production risks by disrupting growing zones and growing days, which depend on precipitation, air temperature, and soil moisture (*very likely, very high confidence*). Growing evidence for positive environmental and economic outcomes of conservation management has led some farmers and ranchers to adopt agroecological practices (*very high confidence*), which increases the potential for agricultural producers to limit greenhouse gas emissions (*likely, medium confidence*) and improve agricultural resilience to climate change (*high confidence*).

Agriculture focuses on the provision of food, feed, fiber, and fuel. Modern agriculture provides essential products engineered for mass production to serve the nutritional, clothing, construction, and energy needs of society. Historically, excessive tillage, heavy reliance on agrochemicals, and simplified cropping systems have led to environmental degradation; therefore, using adaptive conservation management approaches and diversifying agricultural landscapes[3] can build resilience—the ability to anticipate, prepare for, adapt to, withstand, and recover from disruptions like climate change—and improve ecosystem services that affect plant, animal, and human health and well-being (Figure 11.2). Indigenous Knowledge can also play a role in these adaptive approaches (KMs 16.3, 30.5).[4,5]

## Ecosystem Services: Hub of the Wheel

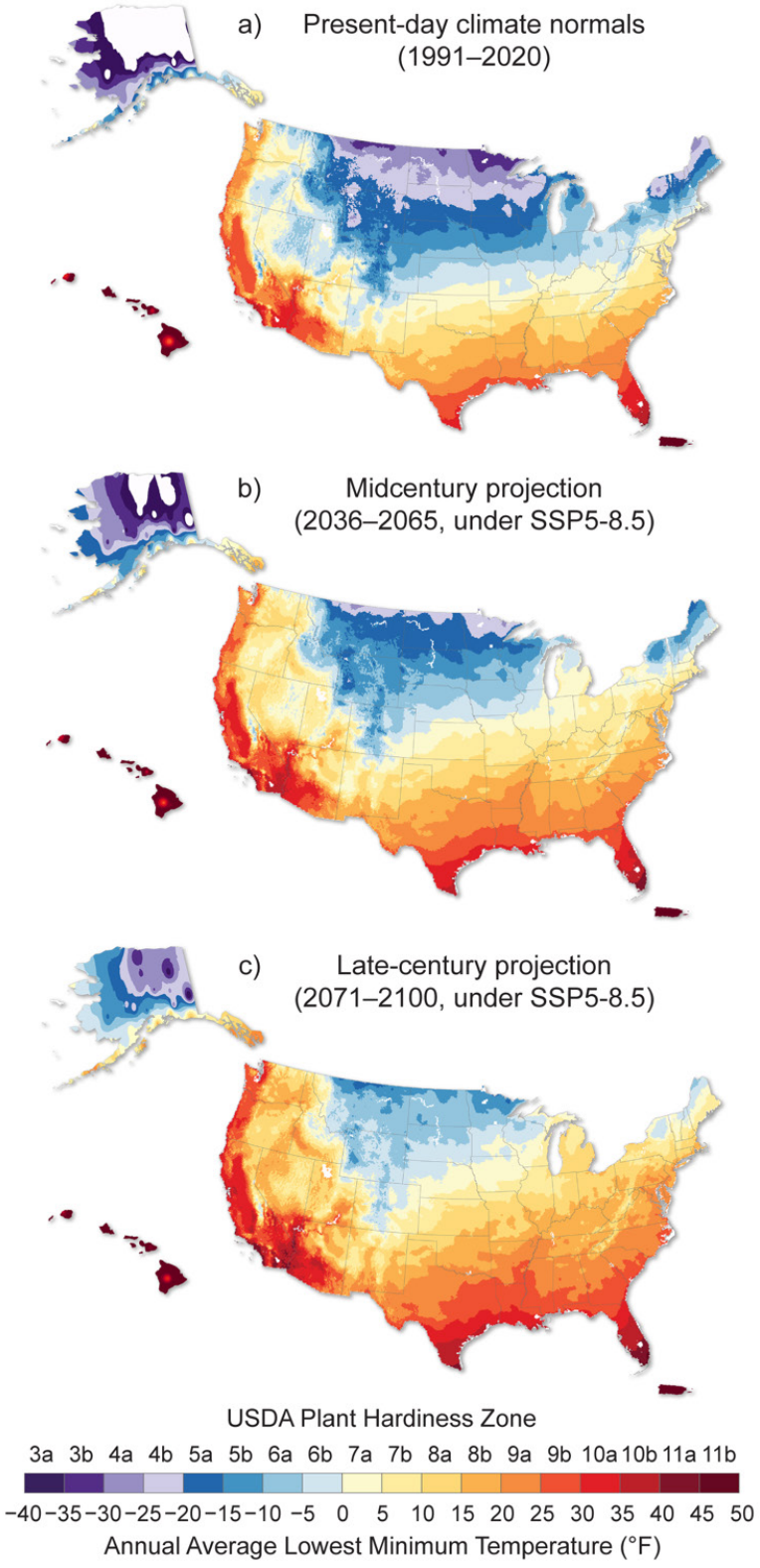



**Ecosystem services have wide-ranging benefits for plants, animals, and human well-being.**

**Figure 11.2.** People receive many benefits from the ecosystem, including provisioning, regulating, supporting, and cultural services. Adaptive management practices (see Figure 8.1) foster resilience to climate change and related disturbances in these ecosystem services (see Figure 8.18). Adapted with permission from MetroVancouver 2018.[6]

Agricultural systems depend on soil, water, air, and sunlight, which vary seasonally and may fluctuate as much as daily. Climate change disrupts these fundamental natural resources. Plant hardiness zones, a common metric for plant appropriateness for a given local climate, have shifted as climate change lengthens frost-free periods (Figure 11.3).[7] Climate shifts, along with greater expected weather volatility, require changes in agricultural practices, including crop selection, use of equipment, and management approaches.

## Projected Changes in Plant Hardiness Zones

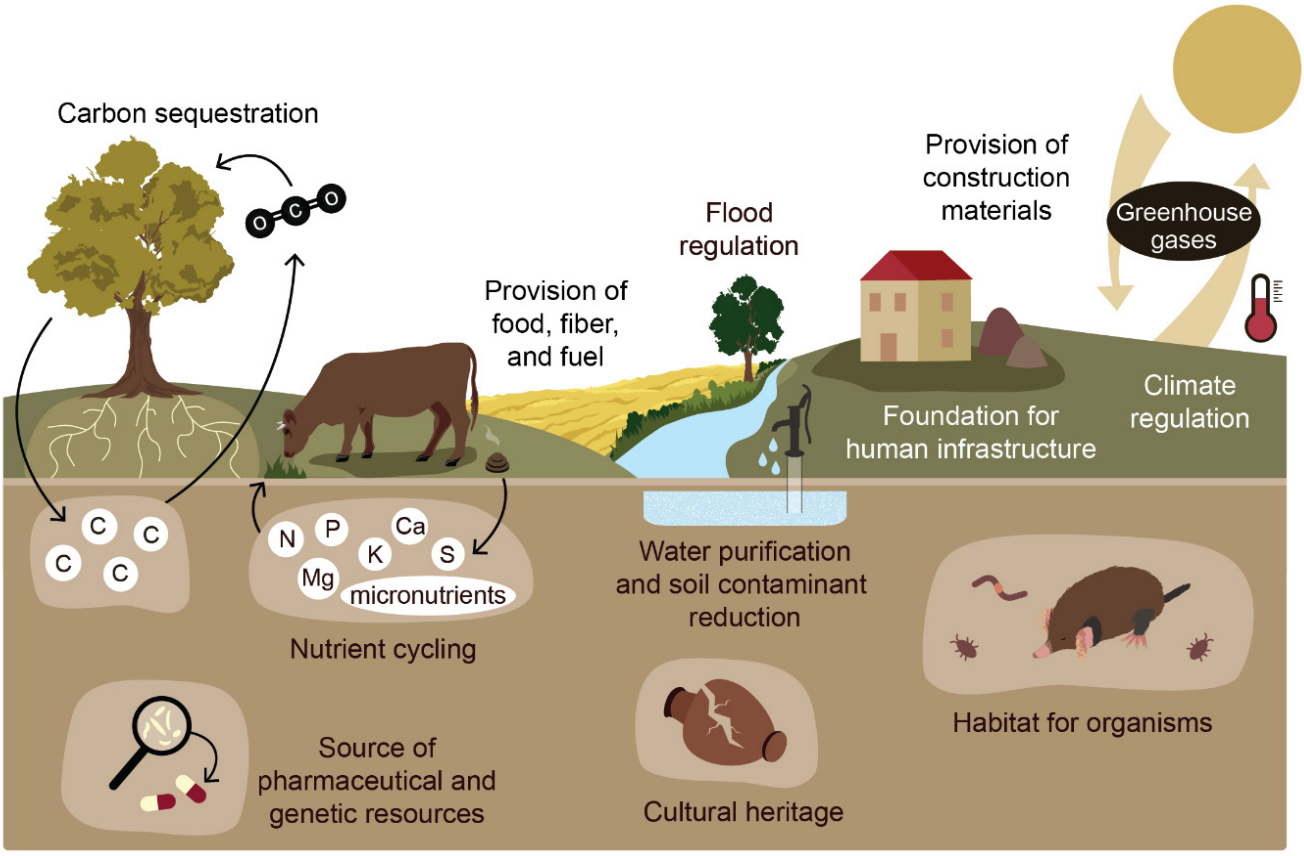



**Plant hardiness zones are projected to shift northward throughout this century.**

**Figure 11.3.** Plant hardiness zones help local farmers and gardeners identify optimal crops to plant and when to plant them. Hardiness zones are projected to migrate northward as the climate warms. The maps show plant hardiness zones for (**a**) present-day (1991–2020) climate normals, and (**b**) midcentury (2036–2065) and (**c**) late century (2071–2100) under a high emissions scenario (SSP5-8.5). Figure credit: USDA, NOAA NCEI, and CISESS NC.

Climate change exacerbates soil degradation through drought, flooding, and excessive heat events that disrupt normal plant production and ecosystem processes. Excessive tillage, overgrazing, and overreliance on agrochemicals can further deplete soil organic matter and impair soil health.[8,9,10,11] Soil health management can improve the resilience of agricultural systems to climate change and support sustainability goals (Figure 11.4).[12] Conservation-based agroecological approaches that improve soil health are increasingly recognized as necessary to maintain productivity while achieving a healthier environment.[13,14,15] While agroecology encompasses ecological, economic, and social dimensions,[16,17,18] the fundamental scientific concept underlying agroecology is the use of ecological principles to sustainably design and manage agricultural systems.[19] Applying agroecological concepts spans a wide range of practices,[18,20] which may overlap with nature-based solutions, precision technologies, and climate-smart agriculture aimed at climate change adaptation and mitigation (Box 11.1; Figure 11.5).[21,22,23,24,25,26] Agroecological practices can also include matching species to the environment, organic matter–driven nutrient cycling, integrated management, and natural pest controls whenever possible,[27,28,29,30] all of which are expected to reduce reliance on synthetic agrochemical inputs. Further, a spatially diverse landscape of croplands, grasslands, forests, and wetlands is expected to support more robust ecosystem functioning (Box 11.1; Figure 11.5).

## Soil as a Foundation




**Healthy soil plays a foundational role in agriculture, ecosystems, society, and culture.**

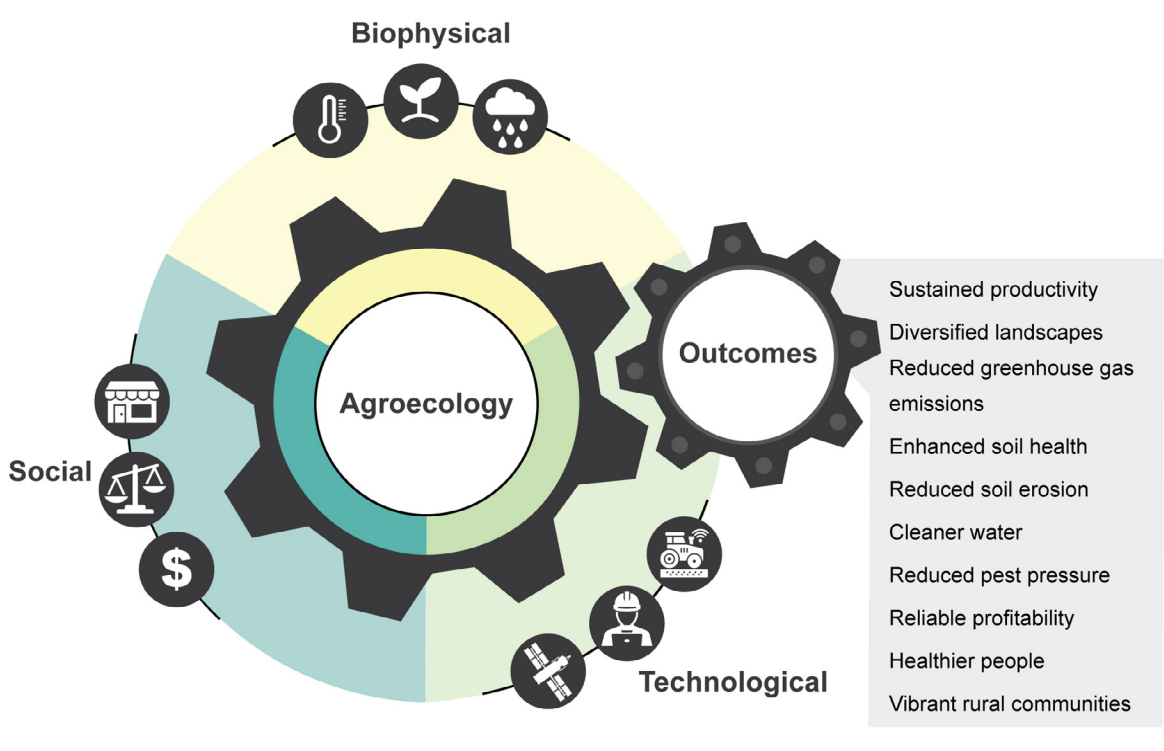
**Figure 11.4.** Healthy soil provides the foundation for many agricultural, ecological, microbiological, societal, and cultural activities. Climate change can negatively affect soil health, thus weakening its foundational role. Adapted from Baveye et al. 2016[31] [CC BY 4.0].

## Box 11.1. Agroecological Approaches to Land Management

Multiple definitions of agroecology exist. As a result, what constitutes an acceptable practice under one definition may be excluded using a different definition. Here, agroecological approaches are defined as land management practices that integrate biophysical, technological, and social concepts and principles to guide the design and management of food and agricultural systems. Agroecological practices include, but are not limited to, 1) improved genetics and breeding, 2) soil health management, 3) integration and diversification of crops and livestock, and 4) precision technologies. Agroecology considers farming practices and management approaches that are developed through a systems science lens, taking into account local conditions and history. Agroecology might include subsistence and organic farming but may also include prudent use of resources through technological interventions. Regardless of scale and level of technological investment, agroecology is the application of science-based ecological concepts and principles to design and manage productive and sustainable agroecosystems. (For a more thorough discussion on agroecology, see Altieri et al. 2015.[32])

Agroecological approaches are used to achieve practical, climate-smart agricultural outcomes balanced with improved ecosystem services and rural livelihoods. Goals of climate-smart agriculture are increased productivity, adaptation to climate change, and reduced greenhouse gas (GHG) emissions.[33] Desired ecosystem services are to mitigate GHG emissions, increase soil carbon, enhance biodiversity, improve environmental quality, and increase agroecosystem adaptability and resilience. Specific practices for climate adaptation are not prescribed; this scientific framework allows practitioners to make decisions reflecting their unique environmental and socioeconomic conditions.

### Agroecology Approaches and Outcomes



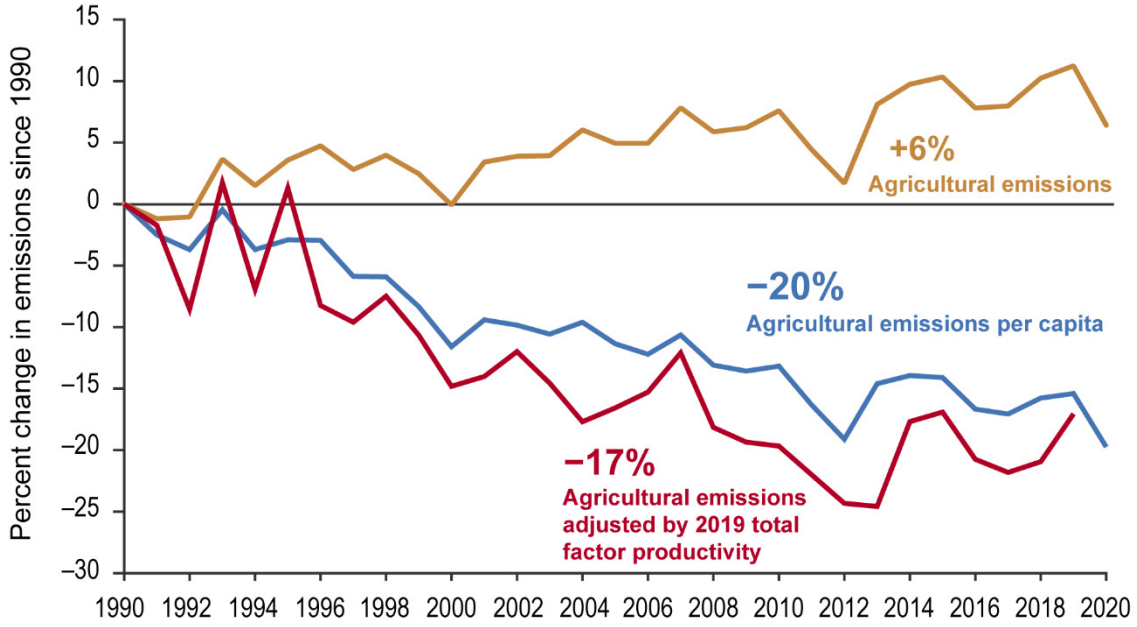

**Agroecological approaches seek to achieve beneficial agricultural outcomes while promoting ecosystem services and rural livelihoods.**

**Figure 11.5.** Science-based application of agroecological approaches results in outcomes that balance agricultural productivity and profitability with ecosystem services and societal well-being. Figure credit: USDA.

Agroecologically based systems promote the transfer of nutrients between living soil components (bacteria, fungi) and non-living soil components (organic matter, minerals) to make nutrients more available to crops and minimize reliance on synthetic fertilizers. Nitrogen fertilizer is a major contributor to emissions of nitrous oxide ($N_2O$), a potent greenhouse gas (GHG). Improving crop nutrient-use efficiency (i.e., increasing crop production per unit of fertilizer used) can reduce input costs for farmers, avoid contamination of water bodies from runoff and leaching, and reduce $N_2O$ contributions to climate change while also making farms more resilient to climatic changes (Figure 11.5).[34,35]

Greenhouse gas emissions from US agriculture over the last three decades have been steadily rising (Figure 11.6). However, economies of scale, enhanced farm technologies, and improved genetics have also increased overall productivity, leading to lower GHG emissions per capita and per unit of total factor productivity (a ratio of agricultural outputs produced to inputs used).

### US Agricultural Greenhouse Gas Emissions Indices, 1990 to 2020




**While total agricultural greenhouse gas emissions continue to increase, emissions per capita and per unit of total factor productivity (a ratio of agricultural outputs produced to inputs used) have declined over the last 30 years.**

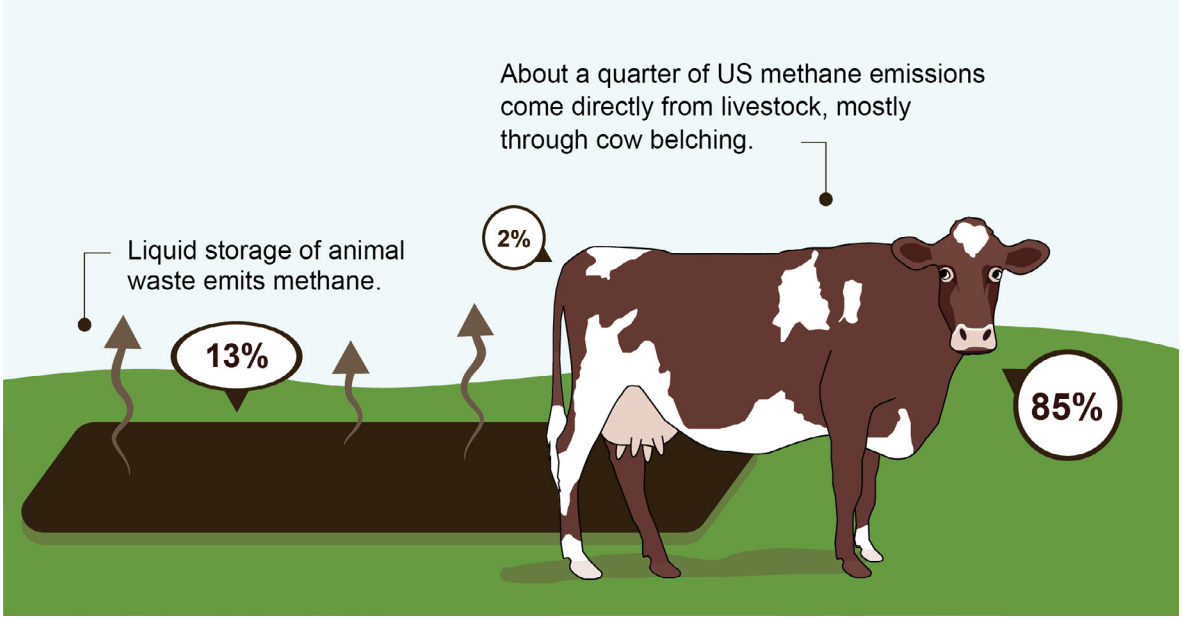
**Figure 11.6.** Over the last 30 years, declines in US agricultural emissions per capita (blue line) and per unit of agricultural productivity (red line) reflect an increasingly efficient US agriculture sector that produces more food, fiber, and renewable fuel with fewer resources. Despite per capita and per unit of productivity improvements, the long-term trajectory of total emissions from US agriculture (yellow line) continues to rise, and mitigation remains a critical priority. Adapted with permission from ©Myers 2022.[36]

Despite greater production efficiencies (KM 11.2), total GHG emissions to the atmosphere continue to increase, and mitigation remains a critical priority (Ch. 32). Agroecological practices often mitigate GHG emissions while providing key adaptation mechanisms to overcome water deficits, improve nutrient cycling, avoid pest pressures, and stabilize production over time.[37,38] Sequestering carbon in agricultural soils has emerged as one strategy to reduce GHG emissions. Land uses and agricultural practices that enhance year-round plant cover and growth convert atmospheric carbon dioxide ($CO_2$) into plant biomass, most of which decomposes and is re-released to the atmosphere as $CO_2$, but a small proportion is

stored as soil organic matter. Because soil loses carbon much faster than it can gain carbon,[39] minimizing disturbance and/or maintaining more stable, persistent plant cover or residues is critical for soil carbon storage and its associated ecosystem services. For example, perennial systems—such as agroforestry that combines grassland with woodland—stimulate carbon storage in soil and in woody vegetation while also supporting greater biodiversity, alleviating heat stress for grazing livestock, and improving watershed management.[40,41,42,43]

Livestock production is impacted by and contributes to climate change by emitting multiple GHGs ($CO_2$, $N_2O$, and methane [$CH_4$]), which vary in amounts by production scale. Livestock producers also face increasingly challenging management decisions due to fluctuations in precipitation, rangeland forage conditions, feed costs, and livestock market prices.[44,45,46] Changing conditions have led to adaptive livestock management, which promotes flexible decision-making while documenting and learning from previous management actions.[47,48] Enteric emissions from livestock production contribute 25% to total US $CH_4$ emissions (Figure 11.7).[49] Some mitigation-reduction options, such as ruminant feed supplements and energy capture from liquid manure systems, have been identified (KM 32.3). Methane is a potent GHG but is generally shorter-lived in the atmosphere (approximately 10 years) than $CO_2$ (months to millennia) and $N_2O$ (116 years; Table 2.1). More accurate accounting of global warming potential that differentiates between long-lived versus short-lived GHGs is expected to improve calculations of future global temperature as well as the non-climate benefits of GHG-specific abatement strategies, especially for $CH_4$ from agriculture.[50,51]

## Cattle-Based Methane Emissions




**Ruminant livestock systems contribute to US methane emissions primarily through belching.**

**Figure 11.7.** Ruminant enteric fermentation via eructation (i.e., belching) contributes most of the methane emissions from US animal production systems (85%), with smaller contributions from manure lagoons (13%) and livestock flatulence (2%). Enteric fermentation contributes approximately 25% of total domestic methane production, making agriculture the largest source of US methane emissions. Figure credit: USDA, NOAA NCEI, and CISESS NC.

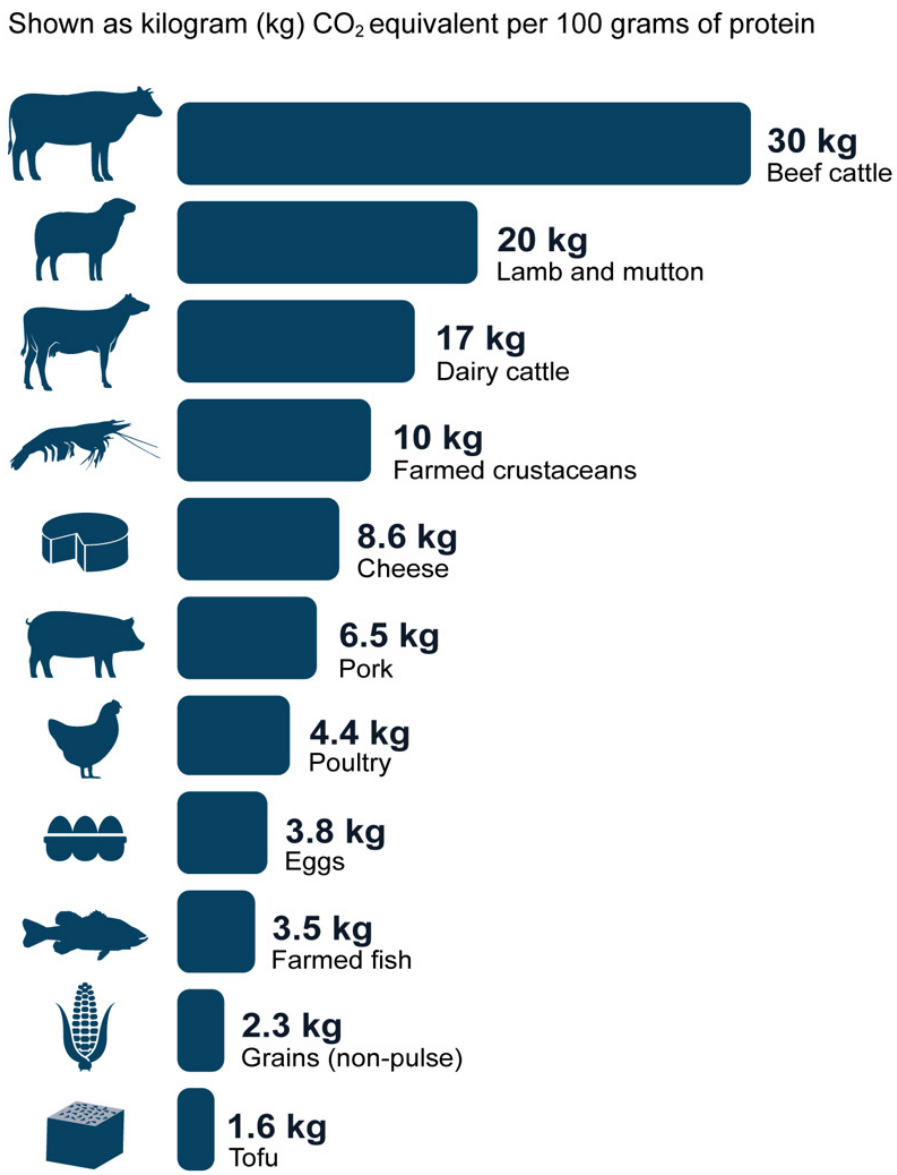
The complexity of climate-related threats and the diversity of agricultural environments in the United States require an array of management approaches. Matching unique regional combinations of plant and animal genetics with regionally relevant management practices can optimize soil carbon sequestration, reduce GHG emissions, and enhance adaptability to a changing climate. Finer-scale precision management aided by digital support tools and artificial intelligence can better account for soil and microclimate variability at farm, field, and subfield levels to maximize results with existing natural resources.

At all spatial and temporal scales, accurate, reliable, and accessible data are critical for effective agricultural management decisions and to improve resilience to climate change. Instrumentation and technology have rapidly evolved but must be harmonized with historical information to guide adaptive management approaches.[52,53] Data collected over longer time periods are necessary to interpret, for example, water availability across periods of drought. Coupling field measurements with computer models can aggregate estimates of productivity, soil carbon changes, biodiversity, and water quality over farms, counties, and regions. Developing these technologies for local, regional, and national scales will help decision-making to address increasing competition among food, water, and energy sectors. To be effective, however, agricultural data on climate-smart practices need to be widely accessible and large in scale.[54]

Rising concerns over food sustainability have driven public interest in alternative production of plant and protein sources, revealing consumer preferences for products that claim reduced GHG emissions. Examples include urban agriculture (e.g., community gardens, food forests, rooftop farms), controlled-environment agriculture (e.g., greenhouses, grow houses, growth chambers), substitution of seafood ("Blue-diet") for livestock-based foods,[55] plant-based meats, and cell-cultivated food production (e.g., cultured meats). These options offer the potential to reduce GHG emissions.[56,57,58,59] However, some approaches can involve more infrastructure or energy inputs per unit of food production, increasing their GHG emissions compared to conventional farming practices.[60] The development, affordability, and sustainability of alternative agricultural systems will depend on social, economic, and environmental factors, as well as institutional constraints (e.g., laws and incentives for creating sustainable systems).[61]

As with terrestrial production practices, innovations in aquaculture have also led to climate-adaptive approaches to protein production. Aquaculture's high feed-conversion efficiency (i.e., unit of protein produced per unit of feed)[62] and lower overall GHG emissions compared to other animal proteins (Figure 11.8)[63] highlight its climate-smart potential to increase protein production, human nutrition, and food availability.[64] Within aquaculture, however, GHG emissions vary by species, with seaweeds and bivalves among the lowest emitters.[65] In addition, location of marine aquaculture and selective breeding can further reduce climate-related impacts.[66] While planned production through aquaculture can buffer climate change disruptions in output from wild-caught fisheries (Ch. 10), rising temperatures, ocean acidification, and sea level rise due to climate change will also limit increases in aquaculture production.[67] Furthermore, complex social and ecological concerns about aquaculture have been raised by some coastal and Indigenous communities. Social concerns include conflict with traditional and commercial livelihoods and consolidation of business activities. Ecological concerns include introducing disease and parasites to wild species, competition between wild and farm-raised species, pollution, and damage to shellfish beds from fish farming, among others (KM 11.3).[68,69]

## Greenhouse Gas Emissions from Protein Production




**Greenhouse gas emissions from protein production vary greatly according to food type.**

**Figure 11.8.** Estimated greenhouse gas (GHG) emissions from protein production vary widely depending on food type. Global median emissions (in kg of carbon dioxide [$CO_2$] equivalents for every 100 g of protein produced) are shown here for 11 major protein sources. Although cereal grains have lower protein content, they are included here because they contribute 41% to global protein intake. While US emissions values may differ slightly from global values, the relative differences in GHG emissions by protein type are expected to be consistent. Figure credit: USDA, NOAA NCEI, and CISESS NC.

Creating resilient agricultural production systems in the face of climate change is possible. Agroecological approaches supported by conservation programs (such as those offered by the USDA through the Natural Resources Conservation Services, Farm Service Agency, and Risk Management Agency)[70] can create rural opportunities (Box 25.3) while optimizing production goals with ecosystem services to store soil carbon, reduce GHG emissions, protect biodiversity, maintain water and air quality, and improve soil and human health by reducing exposure to pollutants. Producers may focus on adaptation to adjust management to climate change and/or on mitigation to store soil organic carbon and reduce GHG emissions.

## Key Message 11.2

## Climate Change Disrupts Our Food Systems in Uneven Ways

Climate change is projected to disrupt food systems in ways that reduce the availability and affordability of nutritious food, with uneven economic impacts across society (*likely*, *medium confidence*). Impacts of climate change on other measures of human well-being are also distributed unevenly, such as worsening heat stress among farmworkers (*high confidence*) and disruptions to the ability of subsistence-based peoples to access food through hunting, fishing, and foraging (*high confidence*).

### *Climate Change Impacts on Food System Security*

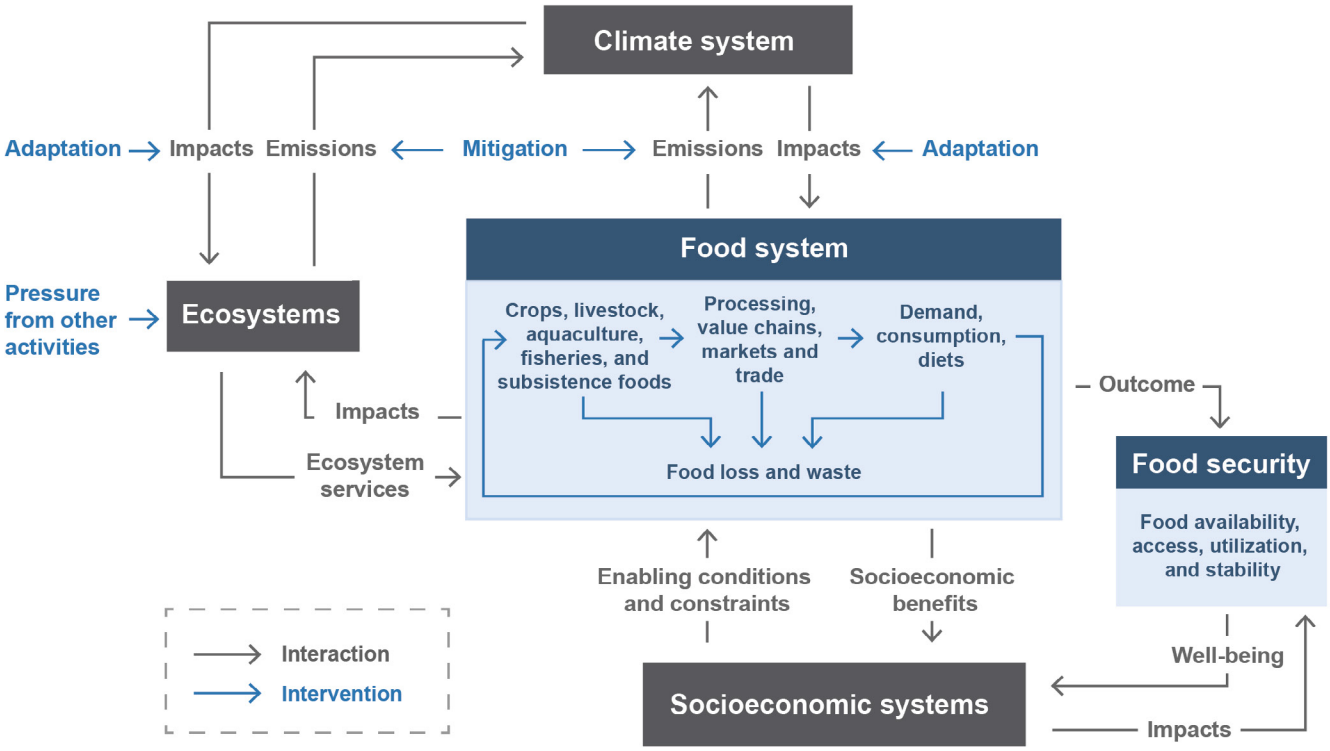
All dimensions of food security—availability, accessibility, utilization (or usability), and stability[71]—are expected to be affected by climate change through long-term changes in average climatic conditions (e.g., annual precipitation and temperature), as well as increases in climate variability and the frequency, magnitude, and duration of climate extremes (Ch. 2). These climatic changes are affecting all aspects of the food supply chain (Figures 11.9, 11.10), including production, storage, processing, distribution, retail, and consumption (Figure F4.1).[72,73] Disruptions to the food supply chain have both local and global impacts on food systems, including food security (Figures 11.11, 23.9).

At local or regional levels, extreme weather events and compound extremes (for example, a heatwave during a drought) are affecting local food security by damaging food production and destroying associated infrastructure (see Focus on Compound Events; KMs 22.4, 28.3).[74,75] These impacts sometimes ripple out to global food systems, impacting prices and availability in other regions of the world.[76,77] At national or international levels, co-occurring extremes and non-climate disruptions (e.g., recessions, pandemics, conflicts) sometimes cascade down to limit food access and availability at local scales throughout the world by reducing supplies, limiting trade, and increasing prices (KM 30.1).[72,78]

Vulnerabilities of food systems to climate change are a function of their complex structures, such as how dependent the systems are on locally grown versus imported foods[79] and how systems respond to changes in climate, ecosystems, and socioeconomic factors (Figures 11.9, 23.9). When widespread shocks occur, local elements of the food system can help insulate communities against some large-scale impacts (KM 30.1). For example, local farmers, mobile meat processors, and food assistance organizations helped insulate their communities against some of the effects of COVID-19-related worker shortages in the commercial food processing and transportation sectors.[78]

Conversely, when a localized shock occurs, interstate, national, and international trade can help fill gaps in food availability (KM 19.2).[79] Each of these local and non-local elements of the food system has unique strengths and weaknesses,[78,80,81] including different impacts on GHG emissions, socioeconomics, and ecosystem goods and services (e.g., carbon storage, biodiversity, water quality; Figure 11.9; Box 11.2).

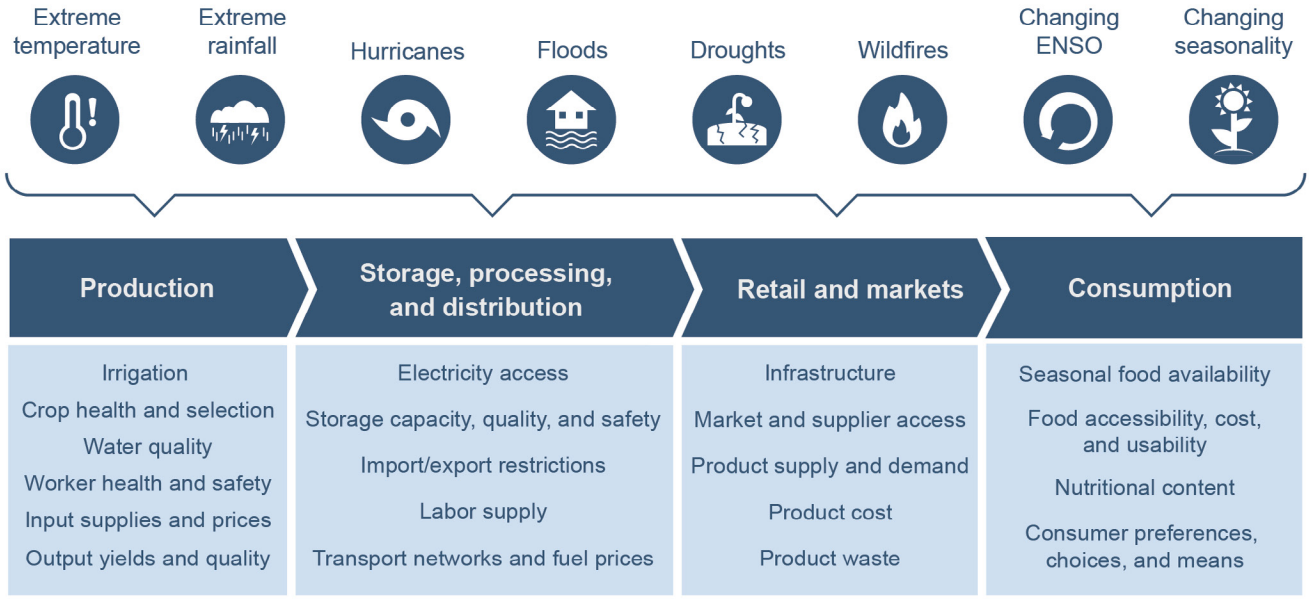
## Connections Between Climate, Food, Ecosystem, and Socioeconomic Systems




**Food security is an outcome of the food system, which influences and is influenced by the climate system, ecosystems, and socioeconomic systems.**

**Figure 11.9.** A food system is a complex network that encompasses all inputs and outputs involved in food production, foraging, harvesting, transport, processing, retailing, consumption, and food loss and waste. There can be different types of food systems, each having impacts on and being impacted by climate, ecosystems, and socioeconomic systems. Interactions between these systems influence human well-being through food security outcomes, such as food availability, access, utilization, and stability. Interventions, such as mitigation and adaptation, can reduce risks to food systems, which improves food security and well-being within socioeconomic systems. Adapted with permission from Figure 5.1 in Mbow et al. 2019.[82]

### Example Effects of Climate Change on the Food Supply Chain




**Climate change has cascading and compounding effects on all stages of the food supply chain.**

**Figure 11.10.** Extreme events fueled by climate change (first row, icons) can affect each stage of the food supply chain (second row, dark blue), resulting in compounding and cascading effects on the food system (third row, light blue). Adapted with permission from Davis et al. 2021.[72]

## *Socioeconomic Costs of Climate Change in Food Systems*

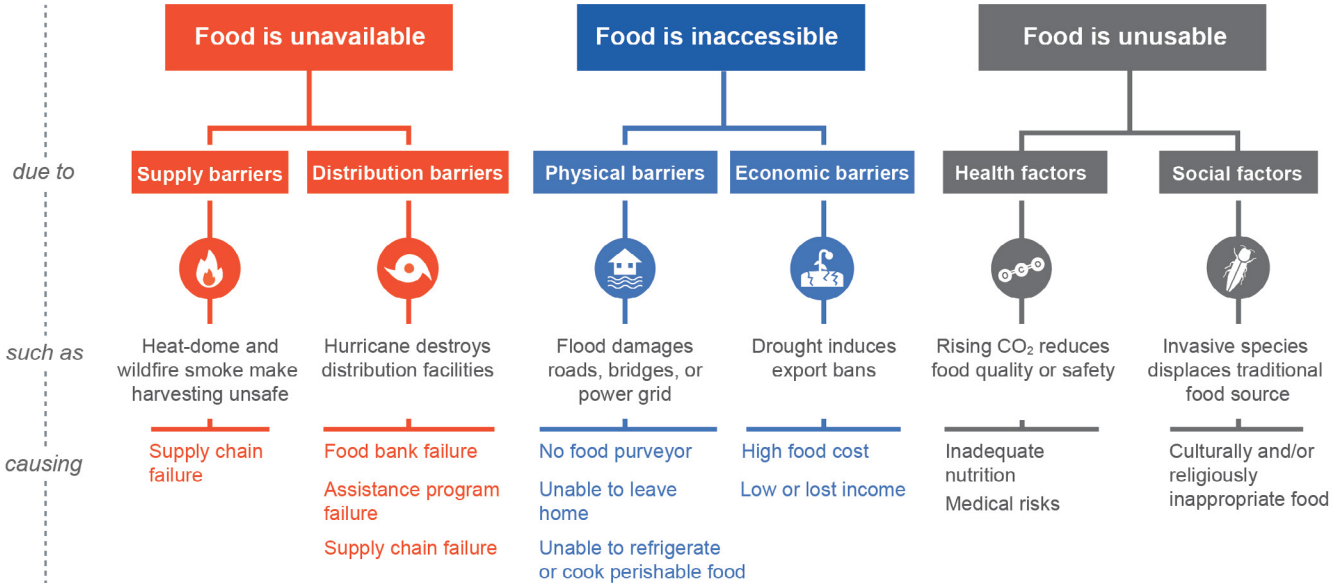
Food security risks from climate change impose socioeconomic costs that workers, producers, and consumers may feel but can be challenging to measure (Ch.15; KM 19.1). Climate change impacts on food production have been measured more comprehensively than impacts on food processing, distribution, marketing, and consumption.[83] For example, climate change is affecting crop insurance costs and losses.[84,85] Between 1991 and 2017, increasing temperature with climate change was responsible for 19% of crop indemnities in the US.[86]

Total factor productivity (TFP) is the focus of several economic studies about the effects of climate change on agriculture.[87] The United States has seen steady growth in agricultural TFP, 1.4% per year since 1948, due largely to technology improvements.[88] While TFP varies annually with extreme weather events, climate change has dampened TFP growth in the United States by 12% over a 54-year period (1961–2015).[89] Agricultural TFP is projected to decline back to pre-1980s levels by 2050 unless the positive effects of innovation and adaptation in US agriculture (after accounting for any negative effects) can be doubled relative to recent historical rates.[88] In the Midwest, greater specialization in crop production has instead caused TFP to become more sensitive to high summer temperatures and soil moisture deficits.[87,90]

Higher temperature and humidity are also affecting farmworker productivity, earnings, and safety, for example, in labor-intensive fruit and vegetable systems (Focus on COVID-19 and Climate Change).[91,92] Heat-related stress and death are significantly greater for farmworkers than for all US civilian workers, and the number of unsafe working days is projected to double by midcentury (Ch. 15; Figure 28.7).[93,94] These effects on farmworker safety and productivity influence the broader economy through reduced agricultural output and higher food prices.[95] Farmworkers also disproportionately experience food insecurity,[2,96] which can be worsened by extreme events fueled by climate change. For example, drought reduces demand for farm labor, thus lowering workers' income and ability to buy food (Ch. 28).[97]

By 2050, climate change is projected to increase some crop prices (see Table 2 of Baker et al. 2018[98]). For example, a 26% price increase is expected for corn due to a 5.5% reduction in production, while a 30% price increase is expected for soybean due to a 19% reduction in production (relative to a no-climate-change baseline and averaged across nine climate change scenarios ranging from a low scenario [RCP2.6] to a scenario slightly higher than a very high scenario [RCP8.5]). A 26% price increase is expected for wheat due to a 36% reduction in production, and a 3.1% price increase is expected for rice due to a 61% reduction in production. Price increases depend on complex interactions between climate change, international trade, and domestic institutions and policies,[80] but they generally benefit producers and hurt consumers (KMs 19.2, 22.3),[99] especially if consumer income cannot keep pace with rising food prices. In such cases, higher food prices can reduce food accessibility (Figures 11.10, 11.11).

### Examples of Food System Failure Due to Climate Change




**Climate change is expected to increase risks to food security in multiple ways.**

**Figure 11.11.** This fault-tree shows some of the many ways that food system failures can occur due to climate change, ultimately making food less accessible, available, or usable. In some cases, food may still be available yet inaccessible or unusable. For example, power outages during extreme heat events or after a hurricane may prevent some consumers from safely refrigerating or cooking perishable foods they have already purchased. Adapted from Chodur et al. (2018)[100] [CC BY 4.0].

## *Climate Change Impacts on Food Security Are Distributed Unevenly*

Climate change interacts with food security and human health (KM 15.1; Figures 11.9, 11.10, 23.4). Approximately 38 million people in the United States live in food-insecure households.[1] Food insecurity is associated with lower income and affects both dietary quality, quantity, and stability.[1] Food system disruptions during increasingly frequent and severe extreme events due to climate change will disproportionately affect food accessibility, nutrition, and health of some groups, including women, children, older adults, and low-wealth communities (KMs 15.2, 22.4, 28.4).[101,102]

For example, if climate change reduces the affordability of some nutritious foods,[98] then households might rely more on calorically dense but nutrient-poor diets, which increase health risks and healthcare costs.[103,104,105] Some older adults who have limited transportation or financial resources face complex challenges and trade-offs when trying to safely access, store, and cook adequate amounts of nutritious food, particularly during and following extreme events (e.g., floods that close roads or stores; KM 11.3).[106,107]

Climate change is also affecting the ability of individuals and communities to obtain food through hunting, fishing, foraging, and subsistence farming (KMs 16.1, 22.1, 25.3, 27.1, 30.1).[108] People from a variety of socioeconomic and cultural backgrounds, including some from Indigenous communities and rural areas, engage in these activities for various reasons, such as cultural or spiritual traditions, medicinal practices, and recreational enjoyment or to diversify food types or nutritional value or reduce purchased foods.[109,110]

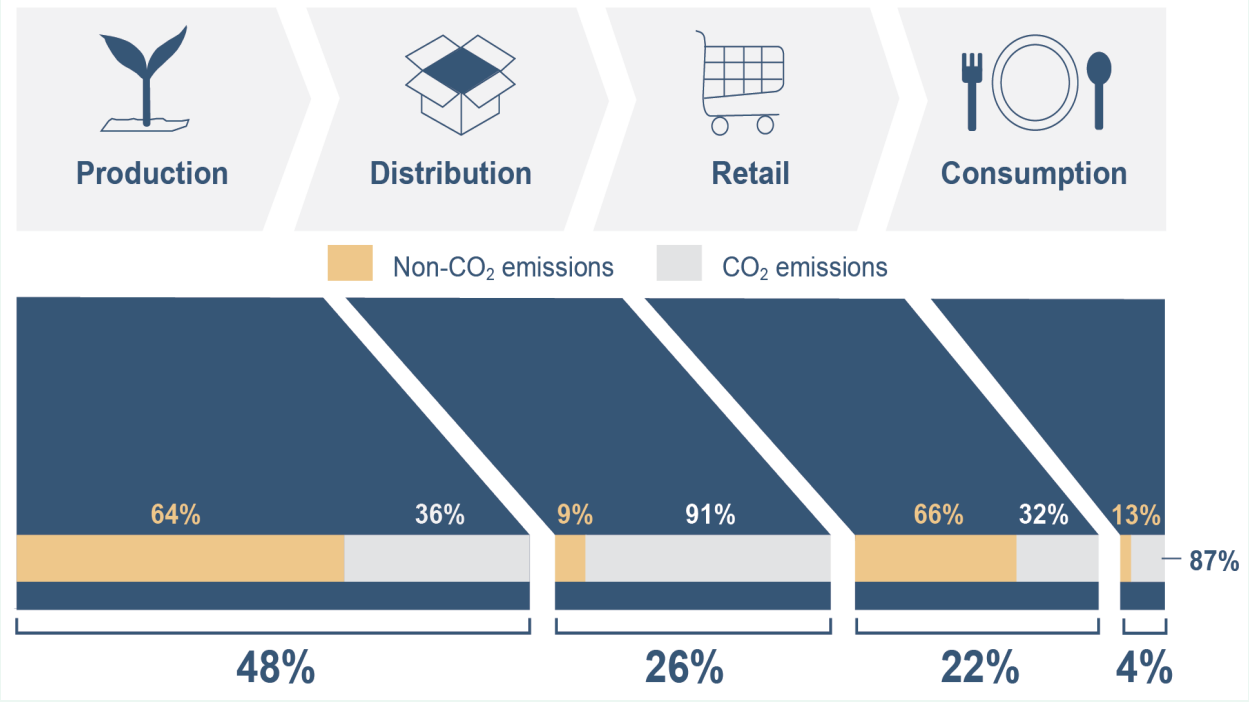
Subsistence-based people who forage for food (such as wild rice, beans, and mushrooms) may face unique challenges from climate change (KMs 16.1, 24.2).[111] Drought can reduce the availability of forest-based foods such as berries, nuts, and seeds. In Alaska, where subsistence hunting and fishing are prevalent among Indigenous Peoples, thinning sea ice makes travel to traditional hunting and fishing/shellfishing grounds longer and more dangerous (Ch. 29). Ecosystem changes reduce the abundance of important species and alter ranges, making it more difficult for people to anticipate those species' locations (KM 29.3).[111]

Subsistence food producers may also be more vulnerable to the effects of climate change due to smaller farm size, insecure land tenure, lower capitalization, and other non-climate stressors (e.g., reduced market access).[112,113] Some communities, however, are proactively leading food security projects to help adapt to and mitigate against climate change (Box 30.4). One example is the Osage Nation's community orchard—informed by Tribal Ecological Knowledge, designed with community health in mind, and providing nutritious fruits, nuts, and berries for community members.[114] Other examples of Tribal adaptation to climate change are described in Key Message 25.5 and Box 29.6.

## Box 11.2. Greenhouse Gas Emissions in the Food System

Most food consumed in the United States is domestically grown, primarily in the Midwest (KM 24.1) and California (KM 28.3).[115,116,117] Production of food is the largest contributor of GHG emissions from the food system, followed by distribution, retail, and consumption (Figure 11.12). Of the total food supply chain (Focus on Risks to Supply Chains), an estimated 30%–40% of food spoils or is wasted, largely at the consumption stage (e.g., households and restaurants).[118,119,120] The further along a supply chain that food waste occurs, the more energy and GHG emissions have been invested. Reducing food loss and waste would reduce food system GHG emissions and provide opportunities to increase food security (KMs 6.3, 32.2; Table 31.1).[120]

### Greenhouse Gas Emissions by Food Supply Chain Stage




**Greenhouse gas emissions differ by stage of the food supply chain.**

**Figure 11.12.** Greenhouse gas (GHG) emissions occur at all stages of the food supply chain. Production (i.e., the growth and harvesting of crops and the rearing and slaughter of livestock) represents 48% of the overall GHG emissions from the food supply chain. Non-carbon dioxide (non-$CO_2$) emissions are largely from nitrous oxide emissions from nitrogen fertilizer and manure management and methane emissions from livestock production in the production stage, along with chlorofluorocarbon emissions at the retail stage. Carbon dioxide emissions in the primary food production stage are from soil and land-use management, fertilizer production, and farm energy use. Energy use is the primary $CO_2$ emissions contributor to supply chain stages downstream from food production. Adapted from EPA (2021).[119]

## Key Message 11.3

## Rural Communities Face Unique Challenges and Opportunities

Rural communities steward much of the Nation's land and natural resources, which provide food, bioproducts, and ecosystem services (*high confidence*). These crucial roles are at risk as climate change compounds existing stressors such as poverty, unemployment, and depopulation (*likely, medium confidence*). Opportunities exist for rural communities to increase their resilience to climate change and protect rural livelihoods (*high confidence*).

Rural (nonmetro) areas comprise over two-thirds of the Nation's total land area[121] and are home to approximately 46.1 million people, or 14% of the total US population, including the majority of Indigenous census respondents. Rural communities represent a way of life with unique environmental assets, cultural heritages, and local identities. Rural populations are stewards of forests, watersheds, rangelands, farmlands, and fisheries and contribute significantly to natural resource conservation and society's benefit and enjoyment of some ecosystem services. Rural communities across these diverse contexts support national economic sustainability and food security.

### Climate Change Risk in Rural America

Climate threats compound risks posed by structural trends such as dependence on goods produced outside the local area, digitization of economic and social life, and demographic change that may reduce resilience and rural quality of life.[122] Budgetary pressures during and after climate-related disasters can reduce local governments' ability to provide critical infrastructure, goods, and services (KM 19.2), especially in under-resourced (Ch. 19; KM 22.1), Indigenous (Ch. 16; KM 25.4), and other historically overburdened (Ch. 20) communities.[123,124,125] The increasing rate and severity of climatic disasters and the compounding and cascading effects of climate change place large economic hardship on local governments and rural communities (KM 2.2),[126,127] although metrics that reflect the complexity of these challenges and their spatial disparities have been historically lacking.

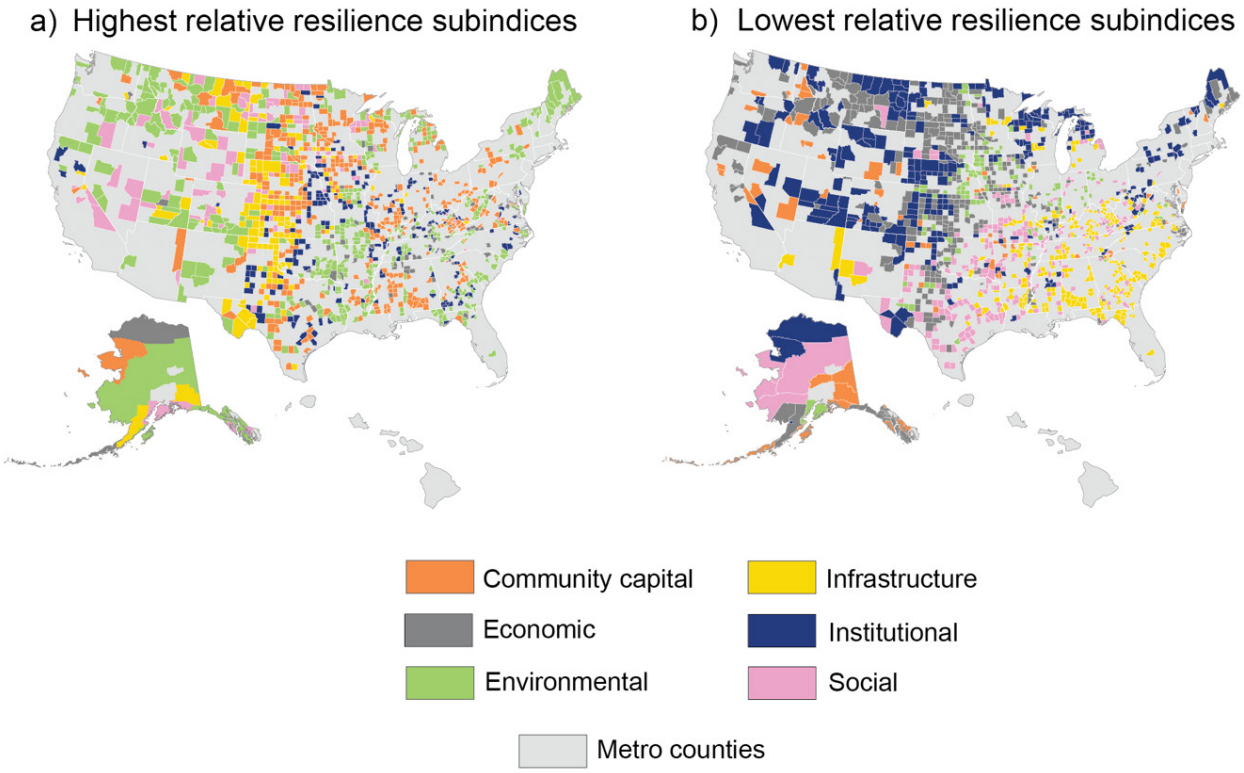
In recent years, there have been significant advances in analytic capabilities for identifying risk variation as influenced by a wide range of social (Ch. 20), economic (KM 22.3), and ecological factors (KM 24.5; Ch. 31). Measures that capture the ability of a community to prepare, adapt, and recover from disruption or disaster indicate greater risk to rural communities than what can be quantified in terms of expected annual loss due to natural hazards alone.[128] This suggests that a broad perspective of rural risk needs to be considered in prioritizing and supporting resilience efforts.

### Rural Community Resilience

There is considerable spatial variability in social, infrastructural, institutional, economic, environmental, and community sources of resilience in rural areas (Figure 11.14). However, most rural communities rank lowest in economic resilience and highest in environmental resilience (Figure 11.13). Resilience encompasses the ability to anticipate, prepare for, adapt to, withstand, and recover from disruptions like climate change. Rural communities have unique sources of and barriers to resilience (Figure 11.14).[123] Resilience is hindered in communities with strained economic and social institutions.[129] Many rural areas struggle to maintain effective government services, economic sustainability, and a strong social base. Demographic and socioeconomic trends, such as population loss and persistent poverty, limit social and economic resilience in some rural areas. These communities lack the capacity or resources needed for recovery in the face of natural hazard events (KM 22.1; Box 25.1). Lack of access to technology and a lack of institutional capacity, for example due to limited financial and human resources, can compound the effects of natural disasters.[130]

Historical environmental justice inequities (Figure 20.1) often underlie and add further complexity to the resilience of rural communities to climate change (Ch. 20; KMs 15.2, 16.2, 26.4, 27.1, 31.2). Rural communities that are characterized by a sense of community, self-reliance, and tacit knowledge of the natural environment have enhanced capacity for resilience (e.g., Box 30.6).

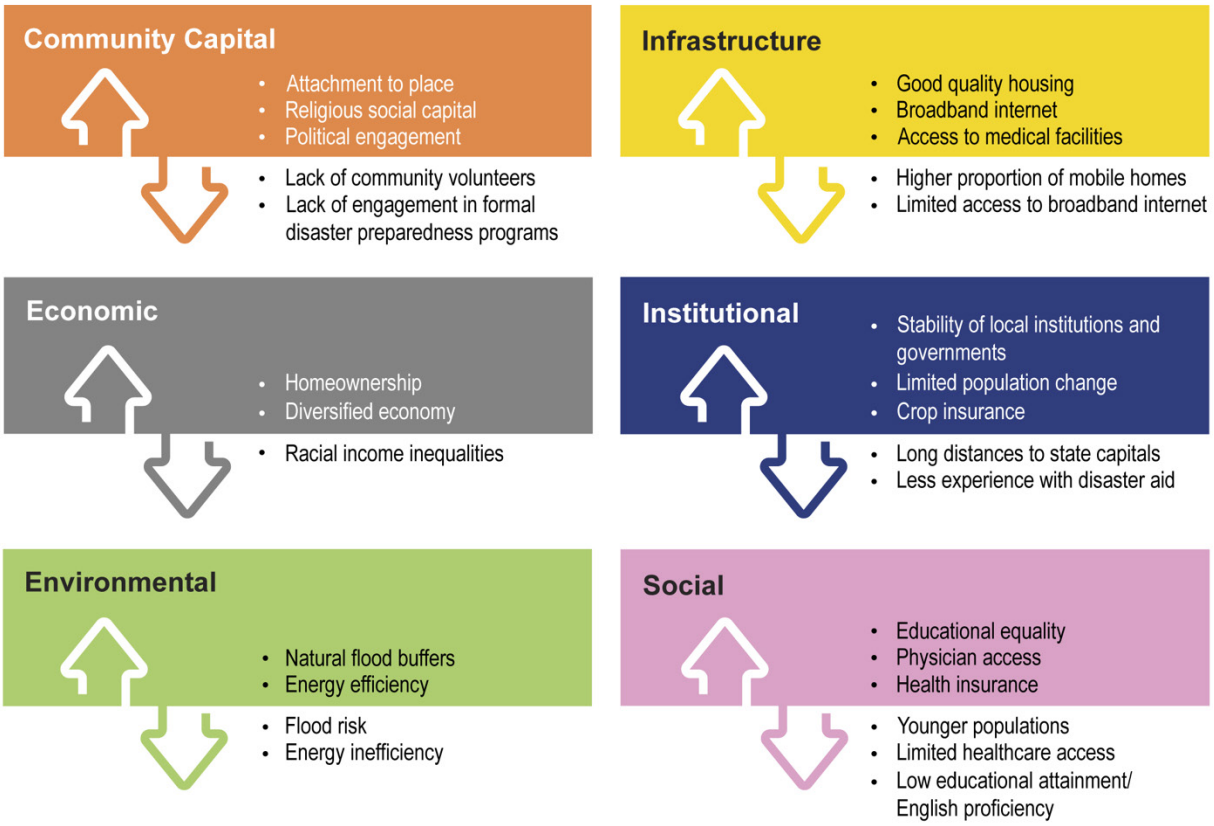
## Community Resilience Index




**Rural communities differ in the categories of the Baseline Resilience Indicators that contribute most substantially to their resilience.**

**Figure 11.13.** Six broad categories (social, economic, community capital, institutional, infrastructure, and environmental) constitute the Baseline Resilience Indicators for Communities (BRIC; see Figure 11.14).[131] The highest (**a**) and lowest (**b**) relative category of resilience for communities within nonmetropolitan counties is shown at the county level. There is considerable spatial variability in each category of community resilience. The US Caribbean and US-Affiliated Pacific Islands are not represented on the map because of a lack of data. Discussion of resilience vulnerabilities for these areas can be found in Chapters 23 and 30. Figure credit: USDA, NOAA NCEI, and CISESS NC.

## Baseline Resilience Indicators for Communities




**Rural community resilience to natural hazards is measured by several broad categories of indicators that affect aspects of resilience (both positively and negatively).**

**Figure 11.14.** The Baseline Resilience Indicators for Communities (BRIC) index is a composite measure of community resilience to natural hazards. It considers 49 indicators of existing attributes of resilience arranged in six broad categories: social, infrastructure, institutional, environmental, economic, and community capital. It can be used to compare community resilience within one county to that of another (see, for example, Figure 11.13). Positive and negative drivers of resilience for rural counties are provided for each category. Figure credit: USDA.

Economic dependence on single-sector or resource-based economies, as often found in rural areas, further constrains resilience (KMs 22.3, 25.3).[122] Many rural jobs are based on resource extraction and dependent on natural resources that are at an increased risk of disruption from climate hazards (e.g., the effects of rising ocean temperature on fisheries and the effects of drought on agriculture). Rural Alaska fishing communities provide a poignant example of how climate impacts compound persistent poverty, geographic isolation, lack of economic diversity, and resource dependence (KM 29.3). A marine heatwave, unprecedented in intensity and duration, hit the Gulf of Alaska from 2014 to 2016, leading to 18 fisheries disaster declarations in the region (Ch. 29).[132,133,134] Climate change is greatly altering the conditions of fishing access and distribution, with increasing collapses that are leaving fishers scrambling for the few alternative income opportunities or taking greater risks to harvest fewer and smaller fish (KM 10.2).[135,136]

While rural communities face challenges, they are also making positive contributions in enhancing climate resilience and mitigating climate change through renewable energy production (KM 5.3). Participatory approaches are needed to ensure that these efforts are equitable and meet community needs. After a natural disaster destroyed the town of Greensburg, Kansas, the community utilized a participatory approach involving multiple rounds of public meetings to engage citizens in planning a sustainable, climate-smart rebuilding process. Emphasis on green materials and Leadership in Energy and Environmental Design

Platinum–certified public buildings allowed the community to rebuild and procure 100% of the energy needed to supply the community through wind energy. Rural communities can contribute to an emerging clean energy economy, including through advanced biofuels[137] and agrivoltaic systems that simultaneously use land for both agriculture and photovoltaic energy production (Chs. 5, 6). Alternative energy sources have the potential to provide a significant portion of US energy needs while also reducing emissions and creating additional jobs and economic opportunity in rural areas.[138]

# Traceable Accounts

## *Process Description*

The chapter lead, with input from the coordinating lead author and agency chapter lead author, recruited the author team exclusively from federal agencies, in accordance with the decision of the National Climate Assessment (NCA) Federal Steering Committee (FSC). The author team was selected to provide expertise on the impacts of climate change on agriculture, food security, and rural communities, with an emphasis on diversity in research expertise, professional experience, and gender. The author team included agricultural, physical, and social scientists. Some were involved with previous Assessments. The author team met weekly to develop and revise drafts throughout the writing process. When disagreements over content, wording, or figures occurred, discussions among the author team occurred until a consensus was reached by the entire author team.

Because this chapter covered a wide range of issues, the author team considered and discussed a broad array of important issues and topics. The Key Messages and topics within each theme were selected after weekly discussions among the authors; a review of the pertinent literature by the author team; review of the Fourth National Climate Assessment and other government reports dealing with climate change and agriculture, food systems, and rural communities; listening sessions organized by the US Global Change Research Program; comments on the Zero Order Draft by the FSC and the public; and comments provided by reviewers on later drafts. A stakeholder public engagement workshop on January 28, 2022, also gave the public an opportunity to provide feedback on proposed Key Messages and topics. Based on these deliberations and feedback from the public, the author team decided to 1) make justice, equity, diversity, and inclusion issues a priority, reflecting the stated goals of the Fifth National Climate Assessment (NCA5); 2) focus on the entire food system rather than just at or behind the farm gate; and 3) reflect growing societal interest in an expanded set of agricultural outcomes beyond agricultural productivity.

The decision to include food systems as a key theme was driven, in part, by the FSC's decision to add "Food Systems" to the NCA5 chapter title. Chapter authors recognized that the US food system is shaped by many factors in addition to on-farm agricultural production. Climate and weather events impact food transportation, processing locations, and waste streams and intensities. Agricultural production is also affected by upstream value chains that influence on-farm production. Therefore, a more holistic approach was taken to understand climate and its changes.

Throughout chapter development, chapter leadership regularly engaged with leads from other relevant chapters to discuss cross-cutting issues and how best to incorporate them among the chapters.

## Key Message 11.1

## Agricultural Adaptation Increases Resilience in an Evolving Landscape

### Description of Evidence Base

#### Agricultural Production at Risk

Extensive peer-reviewed literature has shown that climate change is slowing agricultural productivity and increasing agricultural vulnerability.[84,89,139] Multiple assessments have quantified that increasing air temperatures have lengthened the growing season in the contiguous US by about two weeks.[7] Higher temperatures are projected to lead to greater weather volatility, increased frequency and/or severity of extreme events (drought, frost damage, floods), and greater pest/disease incidence, all of which disrupt crop and livestock growth as well as the timing and effectiveness of agricultural management operations.

### Adoption of Agroecological Practices

A growing number of agricultural studies report that agroecological practices can maintain agricultural productivity while also promoting a broader range of ecosystem services.[13,32,140,141] A recent survey of US farmers showed greater voluntary adoption rates of agroecologically based conservation practices in the last 10 years.[142] While the chapter does not discuss why US producers adopt, retain, or reverse practices, research consistently shows positive correlations between producer adoption of agroecological practices and environmental attitudes, formal education level, and awareness of a program/practice.[143,144,145,146]

### Greenhouse Gas Emissions

The assessment of agricultural contributions to national greenhouse gas (GHG) emissions relied on inventories and estimates from the EPA[49] and were supplemented by data from other federal sources as well as numerous academic studies. Calculations of overall estimated GHG emissions from the agricultural sector among these various sources were comprehensive and in good agreement.

### Mitigation via Agroecological Management

A growing body of evidence shows that adoption of agroecological management practices and technological advances can mitigate agricultural GHG emissions. Soil carbon storage can be increased with no-till cropping and diversification of production systems (e.g., greater crop rotation complexity, perennialization through more grazing lands and/or agroforestry).[147,148] Nitrous oxide and methane emissions can be reduced with improved management (e.g., efficiencies in fertilizer use, water use, and animal grazing and feed).[39,149,150] In addition to increasing the likelihood of GHG mitigation, implementation of such key strategies is projected to reduce dependency on exogenous inputs, protect the environment, and enhance agroecosystem resilience to climate changes.[151,152,153,154]

## Major Uncertainties and Research Gaps

Although climate change impacts on agricultural crop and livestock production are known,[88,155] future effects at the farm, regional, and national scales are uncertain given the variety of adaptation strategies that can be deployed. Further, how these adaptation strategies will interact within highly spatially and temporally variable landscapes (i.e., soils, weather, topography) increase the uncertainty of strategy effectiveness.

Curbing GHG emissions from soil (carbon dioxide [$CO_2$] and nitrous oxide) remains a challenge, because greater production demands are expected to require tillage in some production environments and greater fertilizer inputs to stimulate growth. One major research gap is determining whether and how rapidly practices can be widely deployed to reduce emissions. There is also considerable uncertainty in the capacity of soils to increase carbon storage, given the many interacting factors between management, weather, and landscape properties. Improved livestock diet formulations and integrating livestock into cropping systems could significantly reduce GHG emissions, but scaling issues remain unresolved.

Crop production could be more resilient to climate changes if soils were healthier than at present, but the speed with which such a transformation is possible using an agroecological approach remains unknown.[156,157] Future water availability has a major impact on soil health, and forecasting this will be a challenge.

## Description of Confidence and Likelihood

Confidence is *very high* and it is *very likely* that growing zones and growing days are changing. Historical evidence from a nationally distributed weather network and independent measurement and modeling studies consistently document increasing annual average air temperatures, increasing nighttime temperatures, and greater variability in frost-free periods. The body of evidence indicates an overall migration of growing zones and growing days toward northern latitudes and higher altitudes.

Confidence is *very high* for greater adoption of agroecological practices by producers. Statements on increasing adoption of agroecologically based conservation practices are supported by evidence that agricultural productivity can be maintained and/or increased while improving environmental outcomes.

Confidence is *medium* and it is *likely* that agricultural mitigation strategies will significantly reduce total GHG emissions because there is significant spatial and temporal variability in soils, weather, and type/timing of practices. Measured and modeled literature supports statements that agroecological approaches can increase soil carbon and improve efficiencies will mitigate GHG emissions.

Confidence is *high* that agricultural resilience can be improved in response to climate change. An increasing body of evidence shows that greater stewardship and new economic opportunities (i.e., carbon markets, conservation program cost-shares) can confer greater resilience through improved soil health and resource-use efficiency of external inputs.

## Key Message 11.2

## Climate Change Disrupts Our Food Systems in Uneven Ways

### Description of Evidence Base

#### Food System Resilience

Much of the research on climate change impacts to US food systems, including economics research, focuses more on agricultural production and less on food processing, distribution, marketing, and consumption.[72,83,158] The literature provides some qualitative examples of impacts to these other sectors (e.g., Chodur et al. 2018;[100] Reardon and Zilberman 2018[83]), but the extent is limited and quantitative estimates are rare.

#### Socioeconomic Costs of Climate Change in Food Production

A larger set of literature exists on economic impacts of climate change to agricultural production. Economists have focused particularly on impacts to total factor productivity (TFP) of agriculture, which is the ratio of agricultural outputs produced to the quantity of inputs used.[87,88,89] This literature is mostly consistent in describing the negative impact and general magnitude of climate change effects on US agricultural TFP. Methods are well established, based on broader economic analyses of climate change impacts on productivity of entire economies (not just agriculture; e.g., Letta and Tol 2019[159]).

Also abundant is economics research on climate change and international trade of agricultural products.[80,160] This topic is not covered in depth here but can be summarized as 1) how climate-driven changes in agriculture production around the globe affect US agriculture through international trade[98] and 2) how interstate trade helps dampen economic impacts of climate change on US agriculture.[79]

#### Implications of Climate Change for Food Prices

Basic economic theory on supply, demand, and prices indicates that a reduction in agricultural yields due to climate change, and subsequent reductions in supply of an associated food product (holding all else constant), should increase that food product's price. In reality, complexities arise because not all else is held constant. For example, when wheat yields in the US Central Plains are negatively affected by drought, trade among states and nations dampens the impact on wheat prices. At the same time, consumer incomes and tastes for wheat versus substitute and complementary goods might also change, for entirely separate reasons, making it challenging to quantitatively isolate the effects of climate change on wheat prices.

Due to complexities in markets for agricultural and food products, relatively few economic studies have estimated the effects of climate change on prices of multiple agricultural commodities and food products at a national or international scale. The few studies that have (e.g., Baker et al. 2018;[98] Beach et al. 2015[99]) reached similar conclusions about the direction of impacts and are generally consistent with economic theory (i.e., when supply decreases, holding demand constant, price should rise). It is more difficult to assess the accuracy of the magnitude of their price change estimates.

#### Climate Change Impacts on Food Security Are Distributed Unevenly

Impacts of rising air temperature on outdoor workers' safety and productivity are well understood (Chs. 3, 15).[92] Consistent across multiple studies is that outdoor workers, including farmworkers, will be exposed to more heat stress in the future due to climate change. Disproportionate food insecurity among farmworkers in the US is also well documented in the literature, with consistent findings.[2,96]

The impacts of climate change on home food procurement activities, such as hunting, fishing, foraging, and subsistence farming are well documented in the literature.[110] Regarding impacts to Indigenous Peoples, Norton-Smith et al. (2016)[111] reviewed the literature on this topic and found abundant examples and agreement among studies; more recently, STACCWG (2021)[161] provides numerous examples directly from Tribes and Tribal Peoples.

## Major Uncertainties and Research Gaps

#### Socioeconomic Costs of Climate Change in Food Production

The role of interstate trade in dampening the impacts of climate change has been studied less extensively than the role of international trade, but Dall'Erba et al. (2021)[79] provided a peer-reviewed example of this emerging body of literature.

#### Implications of Climate Change for Food Prices

Major sources of uncertainty in economic modeling of climate change impacts on crop yields and prices result from assumptions about 1) choice of climate models, 2) breadth of impacts from $CO_2$ fertilization, 3) land-use change and yield aggregation, 4) GHG mitigation efforts, and 5) future socioeconomic conditions.[162]

#### Climate Change Impacts on Food Security Are Distributed Unevenly

In studies of food-system workers' exposure to climate change impacts, sources of uncertainty include underreporting of heat-related stress among undocumented workers; variability in individual, workplace, and community risk factors; and future changes in the location of crops and labor needed.[94] There are also relatively few studies documenting or projecting how climate change affects food insecurity among farmworkers or other disproportionately affected groups, such as women, children, and older adults.

## Description of Confidence and Likelihood

The statement about climate change impacts on the affordability of nutritious food is based on a relatively small number of studies about US agricultural TFP, but those reached consistent conclusions about impact direction and magnitude. Conclusions are also consistent with broader research about the separate effects of climate change on yields (or output) and input use. Therefore, confidence is *medium* with a likelihood level of *likely*.

The statement about the magnitude of quantitative impacts on food prices is based on a small number of contemporary studies with many sources of modeling uncertainty about complex national and international markets for agricultural and food products. However, statements about the direction or sign of estimated impacts on food prices, assuming climate change decreases the supply of some agricultural or food products, are consistent with economic theory. Additionally, numerous studies have consistently found that

food price increases have uneven economic impacts across society, with reasonable levels of uncertainty.[163] Therefore, overall confidence about the direction or sign of change in food affordability, with subsequent uneven impacts across society, is *medium*.

The statement about worsening farmworker exposure to heat stress is based on numerous studies with consistent findings and reasonable levels of uncertainty. Confidence is *high*.

The statement about worsening ability to obtain food through hunting, fishing, and foraging is based on numerous studies with consistent findings and reasonable levels of uncertainty. Confidence is *high*.

## Key Message 11.3

## Rural Communities Face Unique Challenges and Opportunities

### Description of Evidence Base

Extensive evidence supports the importance of agriculture as a driver of rural economics and social systems.[164,165] Efforts to conserve the natural resources on which rural communities depend, not only for agriculture but also for other natural amenities–based industries (e.g., recreation and retirement destination), are well documented.[166,167] Ample research documents challenges for rural communities in sustaining their way of life. Challenges include decreasing and aging populations, limited resources available for education and workforce development, limited capital access, infrastructure needs, limited access to healthcare services, and land-use preservation.[168,169,170,171,172,173] Further, many rural communities have high concentrations of socially vulnerable and historically underserved populations. A growing body of research illustrates that these populations are disproportionately at high risk of climate change impacts, which can further exacerbate existing problems.[83,101,123,174,175,176,177]

Community resilience indices (e.g., Baseline Resilience Indicators for Communities) and related metrics (CDC's Social Vulnerability Index, FEMA's National Risk Index for Natural Hazards, and the Census Bureau's Community Resilience Estimates) are increasingly being used to inform community disaster preparedness and climate change adaptation research.[177,178,179,180,181,182] Data to further support this work contribute to an emerging area of study of climate resilience measurement. Recent advances include improvements in small-area estimate methodology (https://www.census.gov/programs-surveys/community-resilience-estimates.html) and emerging public–private partnerships that leverage artificial intelligence and machine learning (e.g., First Street Foundation's Risk Factor and Headwaters Economics' Rural Capacity Map).[183,184,185]

### Major Uncertainties and Research Gaps

Numerous federal, state, and local programs focus on capacity building and specifically provide support and services to rural and underserved communities.[165,186,187] However, there is uncertainty about rural community sustainability and resilience to climate change. Many of the challenges and stressors faced by rural communities are long term, including but not limited to persistent poverty, population loss, an aging population, natural resource depletion, loss of farmland, and limited on- and off-farm economic opportunities.[121,188,189,190,191,192] Further, while many rural communities share similar challenges, they are not socially, culturally, economically, or environmentally homogenous.[193] Greater confidence in the ways communities could successfully adapt to perturbations would require additional research and training from a variety of potential strategies across the diversity of rural communities.

## Description of Confidence and Likelihood

Extensive data show that rural communities support agricultural systems, which provide essential sources of food, fuel, feed, and fiber. Rural communities and their residents manage more than two-thirds of US land[194] and thus bear responsibility for protecting the natural resources and ecosystem services and disservices they provide. Confidence is *high*.

Extensive evidence indicates that climate change and its compounding effects exacerbate existing stressors such as poverty, limited revenue, unemployment, and depopulation on rural communities. However, studies on the impact and extent of these detrimental impacts on the ability of these communities to continue to provide food, fuel, feed, and fiber resources to the Nation are less numerous. Evidence indicating that these communities will lose the ability to manage natural resources and maintain current levels of ecosystem services is limited. Confidence is *medium* with a likelihood level of *likely*.

Evidence from numerous communities documents the existence of opportunities for rural communities to increase climate change resilience. However, future climate change impacts on rural livelihoods and the long-term efficacy of rural resilience efforts are uncertain. Significant variability exists in the challenges and needs of individual rural communities.[195] Confidence is *high*.

# References


1. Coleman-Jensen, A., M.P. Rabbitt, C.A. Gregory, and A. Singh, 2021: Household Food Security in the United States in 2020. ERR-298. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=102075

2. Meierotto, L., T. Mares, and S.M. Holmes, 2020: Introduction to the symposium: Bienestar—the well-being of Latinx farmworkers in a time of change. *Agriculture and Human Values*, **37** (1), 187–196. https://doi.org/10.1007/s10460-019-09964-9

3. Basso, B., 2021: Precision conservation for a changing climate. *Nature Food*, **2** (5), 322–323. https://doi.org/10.1038/s43016-021-00283-z

4. Imoro, Z.A., A.Z. Imoro, A.B. Duwiejuah, and A. Abukari, 2021: Harnessing Indigenous technologies for sustainable management of land, water, and food resources amidst climate change. *Frontiers in Sustainable Food Systems*, **5**, 691603. https://doi.org/10.3389/fsufs.2021.691603

5. Melash, A.A., A.A. Bogale, A.T. Migbaru, G.G. Chakilu, A. Percze, É.B. Ábrahám, and D.K. Mengistu, 2023: Indigenous agricultural knowledge: A neglected human based resource for sustainable crop protection and production. *Heliyon*, **9** (1), e12978. https://doi.org/10.1016/j.heliyon.2023.e12978

6. Metro Vancouver, 2018: Ecological Health Framework. Metro Vancouver. https://metrovancouver.org/services/regional-planning/Documents/ecological-health-framework.pdf#search=Ecological%20Health%20Framework%2E

7. Kukal, M.S. and S. Irmak, 2018: U.S. agro-climate in 20th century: Growing degree days, first and last frost, growing season length, and impacts on crop yields. *Scientific Reports*, **8** (1), 6977. https://doi.org/10.1038/s41598-018-25212-2

8. Franzluebbers, A.J., 2013: Introduction to themed section—Supporting ecosystem services with conservation agricultural approaches. *Renewable Agriculture and Food Systems*, **28** (2), 99–101. https://doi.org/10.1017/s1742170513000021

9. Ghimire, R., U. Norton, P. Bista, A.K. Obour, and J.B. Norton, 2017: Soil organic matter, greenhouse gases and net global warming potential of irrigated conventional, reduced-tillage and organic cropping systems. *Nutrient Cycling in Agroecosystems*, **107** (1), 49–62. https://doi.org/10.1007/s10705-016-9811-0

10. Jakab, G., B. Madarász, M. Masoudi, M. Karlik, C. Király, D. Zacháry, T. Filep, I. Dekemati, C. Centeri, T. Al-Graiti, and Z. Szalai, 2023: Soil organic matter gain by reduced tillage intensity: Storage, pools, and chemical composition. *Soil and Tillage Research*, **226**, 105584. https://doi.org/10.1016/j.still.2022.105584

11. Krauss, M., A. Berner, F. Perrochet, R. Frei, U. Niggli, and P. Mäder, 2020: Enhanced soil quality with reduced tillage and solid manures in organic farming—A synthesis of 15 years. *Scientific Reports*, **10** (1), 4403. https://doi.org/10.1038/s41598-020-61320-8

12. Lehmann, J., D.A. Bossio, I. Kögel-Knabner, and M.C. Rillig, 2020: The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, **1** (10), 544–553. https://doi.org/10.1038/s43017-020-0080-8

13. Franzluebbers, A.J., 2020: Soil-test biological activity with the flush of $CO_2$: V. Validation of nitrogen prediction for corn production. *Agronomy Journal*, **112** (3), 2188–2204. https://doi.org/10.1002/agj2.20094

14. Franzluebbers, A.J. and G. Martin, 2022: Farming with forages can reconnect crop and livestock operations to enhance circularity and foster ecosystem services. *Grass and Forage Science*, **77** (4), 270–281. https://doi.org/10.1111/gfs.12592

15. Palomo-Campesino, S., M. García-Llorente, V. Hevia, F. Boeraeve, N. Dendoncker, and J.A. González, 2022: Do agroecological practices enhance the supply of ecosystem services? A comparison between agroecological and conventional horticultural farms. *Ecosystem Services*, **57**, 101474. https://doi.org/10.1016/j.ecoser.2022.101474

16. Francis, C., G. Lieblein, S. Gliessman, T.A. Breland, N. Creamer, R. Harwood, L. Salomonsson, J. Helenius, D. Rickerl, R. Salvador, M. Wiedenhoeft, S. Simmons, P. Allen, M. Altieri, C. Flora, and R. Poincelot, 2003: Agroecology: The ecology of food systems. *Journal of Sustainable Agriculture*, **22** (3), 99–118. https://doi.org/10.1300/J064v22n03_10

17. Rivera-Ferre, M.G., 2018: The resignification process of Agroecology: Competing narratives from governments, civil society and intergovernmental organizations. *Agroecology and Sustainable Food Systems*, **42** (6), 666–685. https://doi.org/10.1080/21683565.2018.1437498

18. Wezel, A., M. Casagrande, F. Celette, J.-F. Vian, A. Ferrer, and J. Peigné, 2014: Agroecological practices for sustainable agriculture. A review. *Agronomy for Sustainable Development*, **34** (1), 1–20. https://doi.org/10.1007/s13593-013-0180-7

19. Gliessman, S.R., 2014: *Agroecology: The Ecology of Sustainable Food Systems*, 3rd ed. CRC Press, Boca Raton, FL, 405 pp. https://doi.org/10.1201/b17881

20. Bezner Kerr, R., S. Madsen, M. Stüber, J. Liebert, S. Enloe, N. Borghino, P. Parros, D.M. Mutyambai, M. Prudhon, and A. Wezel, 2021: Can agroecology improve food security and nutrition? A review. *Global Food Security*, **29**, 100540. https://doi.org/10.1016/j.gfs.2021.100540

21. Amoak, D., I. Luginaah, and G. McBean, 2022: Climate change, food security, and health: Harnessing agroecology to build climate-resilient communities. *Sustainability*, **14** (21), 13954. https://doi.org/10.3390/su142113954

22. Duff, H., P.B. Hegedus, S. Loewen, T. Bass, and B.D. Maxwell, 2022: Precision agroecology. *Sustainability*, **14** (1), 106. https://doi.org/10.3390/su14010106

23. Hrabanski, M. and J.F. Le Coq, 2022: Climatisation of agricultural issues in the international agenda through three competing epistemic communities: Climate-smart agriculture, agroecology, and nature-based solutions. *Environmental Science & Policy*, **127**, 311–320. https://doi.org/10.1016/j.envsci.2021.10.022

24. Maurel, V.B. and C. Huyghe, 2017: Putting agricultural equipment and digital technologies at the cutting edge of agroecology. OCL, **24** (3), D307. https://doi.org/10.1051/ocl/2017028

25. Vagge, I. and G. Chiaffarelli, 2023: Validating the contribution of nature-based farming solutions (NBFS) to agrobiodiversity values through a multi-scale landscape approach. *Agronomy*, **13** (1). https://doi.org/10.3390/agronomy13010233

26. Wynberg, R., M. Pimbert, N. Moeller, G. McAllister, R.B. Kerr, J. Singh, M. Belay, and M. Ngcoya, 2023: Nature-based solutions and agroecology: Business as usual or an opportunity for transformative change? *Environment: Science and Policy for Sustainable Development*, **65** (1), 15–22. https://doi.org/10.1080/00139157.2023.2146944

27. Martin, A.R. and M.E. Isaac, 2018: Functional traits in agroecology: Advancing description and prediction in agroecosystems. *Journal of Applied Ecology*, **55** (1), 5–11. https://doi.org/10.1111/1365-2664.13039

28. National Academies of Sciences, Engineering, and Medicine, 2019: *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* The National Academies Press, Washington, DC, 510 pp. https://doi.org/10.17226/25259

29. Tittonell, P., G. Piñeiro, L.A. Garibaldi, S. Dogliotti, H. Olff, and E.G. Jobbagy, 2020: Agroecology in large scale farming—A research agenda. *Frontiers in Sustainable Food Systems*, **4**, 584605. https://doi.org/10.3389/fsufs.2020.584605

30. Wezel, A., B.G. Herren, R.B. Kerr, E. Barrios, A.L.R. Gonçalves, and F. Sinclair, 2020: Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, **40** (6), 40. https://doi.org/10.1007/s13593-020-00646-z

31. Baveye, P.C., J. Baveye, and J. Gowdy, 2016: Soil "ecosystem" services and natural capital: Critical appraisal of research on uncertain ground. *Frontiers in Environmental Science*, **4**, 41. https://doi.org/10.3389/fenvs.2016.00041

32. Altieri, M.A., C.I. Nicholls, A. Henao, and M.A. Lana, 2015: Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development*, **35** (3), 869–890. https://doi.org/10.1007/s13593-015-0285-2

33. USDA, n.d.: The Role of Climate-Smart Agriculture in Climate Adaptation and Mitigation in the Northeast. U.S. Department of Agriculture, Climate Hubs, accessed August 4, 2023. https://www.climatehubs.usda.gov/hubs/northeast/topic/role-climate-smart-agriculture-climate-adaptation-and-mitigation-northeast

34. Mizik, T., 2021: Climate-smart agriculture on small-scale farms: A systematic literature review. *Agronomy*, **11** (6), 1096. https://doi.org/10.3390/agronomy11061096

35. Prager, K., J. Schuler, K. Helming, P. Zander, T. Ratinger, and K. Hagedorn, 2011: Soil degradation, farming practices, institutions and policy responses: An analytical framework. *Land Degradation & Development*, **22** (1), 32–46. https://doi.org/10.1002/ldr.979

36. Myers, S., 2022: 2020 EPA Emissions Inventory Demonstrates Agriculture's Advancements in Sustainability. American Farm Bureau Federation. https://www.fb.org/market-intel/2020-epa-emissions-inventory-demonstrates-agricultures-advancements-in-sustainability

37. Abdalla, M., A. Hastings, K. Cheng, Q. Yue, D. Chadwick, M. Espenberg, J. Truu, R.M. Rees, and P. Smith, 2019: A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global Change Biology*, **25** (8), 2530–2543. https://doi.org/10.1111/gcb.14644

38. Ogle, S.M., C. Alsaker, J. Baldock, M. Bernoux, F.J. Breidt, B. McConkey, K. Regina, and G.G. Vazquez-Amabile, 2019: Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. *Scientific Reports*, **9** (1), 11665. https://doi.org/10.1038/s41598-019-47861-7

39. Sanderson, J.S., C. Beutler, J.R. Brown, I. Burke, T. Chapman, R.T. Conant, J.D. Derner, M. Easter, S.D. Fuhlendorf, G. Grissom, J.E. Herrick, D. Liptzin, J.A. Morgan, R. Murph, C. Pague, I. Rangwala, D. Ray, R. Rondeau, T. Schulz, and T. Sullivan, 2020: Cattle, conservation, and carbon in the western Great Plains. *Journal of Soil and Water Conservation*, **75** (1), 5A–12A. https://doi.org/10.2489/jswc.75.1.5a

40. Aryal, D.R., D.E. Morales-Ruiz, S. López-Cruz, C.N. Tondopó-Marroquín, A. Lara-Nucamendi, J.A. Jiménez-Trujillo, E. Pérez-Sánchez, J.E. Betanzos-Simon, F. Casasola-Coto, A. Martínez-Salinas, C.J. Sepúlveda-López, R. Ramírez-Díaz, M.A. La O Arias, F. Guevara-Hernández, R. Pinto-Ruiz, and M. Ibrahim, 2022: Silvopastoral systems and remnant forests enhance carbon storage in livestock-dominated landscapes in Mexico. *Scientific Reports*, **12** (1), 16769. https://doi.org/10.1038/s41598-022-21089-4

41. Howlett, D.S., M.R. Mosquera-Losada, P.K.R. Nair, V.D. Nair, and A. Rigueiro-Rodríguez, 2011: Soil carbon storage in silvopastoral systems and a treeless pasture in northwestern Spain. *Journal of Environmental Quality*, **40** (3), 825–832. https://doi.org/10.2134/jeq2010.0145

42. Lorenz, K. and R. Lal, 2014: Soil organic carbon sequestration in agroforestry systems. A review. *Agronomy for Sustainable Development*, **34** (2), 443–454. https://doi.org/10.1007/s13593-014-0212-y

43. Mayer, S., M. Wiesmeier, E. Sakamoto, R. Hübner, R. Cardinael, A. Kühnel, and I. Kögel-Knabner, 2022: Soil organic carbon sequestration in temperate agroforestry systems—A meta-analysis. *Agriculture, Ecosystems & Environment*, **323**, 107689. https://doi.org/10.1016/j.agee.2021.107689

44. Augustine, D.J., 2010: Spatial versus temporal variation in precipitation in a semiarid ecosystem. *Landscape Ecology*, **25** (6), 913–925. https://doi.org/10.1007/s10980-010-9469-y

45. Derner, J.D. and D.J. Augustine, 2016: Adaptive management for drought on rangelands. *Rangelands*, **38** (4), 211–215. https://doi.org/10.1016/j.rala.2016.05.002

46. Shrum, T.R., W.R. Travis, T.M. Williams, and E. Lih, 2018: Managing climate risks on the ranch with limited drought information. *Climate Risk Management*, **20**, 11–26. https://doi.org/10.1016/j.crm.2018.01.002

47. Allen, C.R. and L.H. Gunderson, 2011: Pathology and failure in the design and implementation of adaptive management. *Journal of Environmental Management*, **92** (5), 1379–1384. https://doi.org/10.1016/j.jenvman.2010.10.063

48. Fernandez-Gimenez, M.E., H.L. Ballard, and V.E. Sturtevant, 2008: Adaptive management and social learning in collaborative and community-based monitoring: A study of five community-based forestry organizations in the western USA. *Ecology and Society*, **13** (2). https://doi.org/10.5751/es-02400-130204

49. EPA, 2023: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021. EPA 430-R-23-002. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021

50. Allen, M.R., G.P. Peters, K.P. Shine, C. Azar, P. Balcombe, O. Boucher, M. Cain, P. Ciais, W. Collins, P.M. Forster, D.J. Frame, P. Friedlingstein, C. Fyson, T. Gasser, B. Hare, S. Jenkins, S.P. Hamburg, D.J.A. Johansson, J. Lynch, A. Macey, J. Morfeldt, A. Nauels, I. Ocko, M. Oppenheimer, S.W. Pacala, R. Pierrehumbert, J. Rogelj, M. Schaeffer, C.F. Schleussner, D. Shindell, R.B. Skeie, S.M. Smith, and K. Tanaka, 2022: Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. *npj Climate and Atmospheric Science*, **5** (1), 5. https://doi.org/10.1038/s41612-021-00226-2

51. Smith, M.A., M. Cain, and M.R. Allen, 2021: Further improvement of warming-equivalent emissions calculation. *npj Climate and Atmospheric Science*, **4** (1), 19. https://doi.org/10.1038/s41612-021-00169-8

52. Claverie, M., J. Ju, J.G. Masek, J.L. Dungan, E.F. Vermote, J.-C. Roger, S.V. Skakun, and C. Justice, 2018: The Harmonized Landsat and Sentinel-2 surface reflectance data set. *Remote Sensing of Environment*, **219**, 145–161. https://doi.org/10.1016/j.rse.2018.09.002

53. Sloat, L.L., S.J. Davis, J.S. Gerber, F.C. Moore, D.K. Ray, P.C. West, and N.D. Mueller, 2020: Climate adaptation by crop migration. *Nature Communications*, **11** (1), 1243. https://doi.org/10.1038/s41467-020-15076-4

54. Oloo, A.S., 2020: Service-oriented data mining architecture for climate-smart agriculture. *American Journal of Data Mining and Knowledge Discovery*, **5** (1), 1–10. https://doi.org/10.11648/j.ajdmkd.20200501.11

55. Coleman, J., 2022: Eat more fish: When switching to seafood helps—and when it doesn't. *Nature*. https://doi.org/10.1038/d41586-022-02928-w

56. Apostolidis, C. and F. McLeay, 2019: To meat or not to meat? Comparing empowered meat consumers' and anti-consumers' preferences for sustainability labels. *Food Quality and Preference*, **77**, 109–122. https://doi.org/10.1016/j.foodqual.2019.04.008

57. Bangsa, A.B. and B.B. Schlegelmilch, 2020: Linking sustainable product attributes and consumer decision-making: Insights from a systematic review. *Journal of Cleaner Production*, **245**, 118902. https://doi.org/10.1016/j.jclepro.2019.118902

58. Chen, X., Z. Gao, and B.R. McFadden, 2020: Reveal preference reversal in consumer preference for sustainable food products. *Food Quality and Preference*, **79**, 103754. https://doi.org/10.1016/j.foodqual.2019.103754

59. Clune, S., E. Crossin, and K. Verghese, 2017: Systematic review of greenhouse gas emissions for different fresh food categories. *Journal of Cleaner Production*, **140**, 766–783. https://doi.org/10.1016/j.jclepro.2016.04.082

60. McDougall, R., P. Kristiansen, and R. Rader, 2019: Small-scale urban agriculture results in high yields but requires judicious management of inputs to achieve sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (1), 129–134. https://doi.org/10.1073/pnas.1809707115

61. Pearson, L.J., L. Pearson, and C.J. Pearson, 2010: Sustainable urban agriculture: Stocktake and opportunities. *International Journal of Agricultural Sustainability*, **8** (1–2), 7–19. https://doi.org/10.3763/ijas.2009.0468

62. Waite, R., M. Beveridge, R. Brummett, S. Castine, N. Chaiyawannakarn, S. Kaushik, R. Mungkung, S. Nawapakpilai, and M. Phillips, 2014: Improving Productivity and Environmental Performance of Aquaculture. World Resources Institute, Washington, DC, 60 pp. https://www.wri.org/research/improving-productivity-and-environmental-performance-aquaculture

63. MacLeod, M.J., M.R. Hasan, D.H.F. Robb, and M. Mamun-Ur-Rashid, 2020: Quantifying greenhouse gas emissions from global aquaculture. *Scientific Reports*, **10** (1), 11679. https://doi.org/10.1038/s41598-020-68231-8

64. Ahmed, N. and S. Thompson, 2019: The blue dimensions of aquaculture: A global synthesis. *Science of The Total Environment*, **652**, 851–861. https://doi.org/10.1016/j.scitotenv.2018.10.163

65. Gephart, J.A., P.J.G. Henriksson, R.W.R. Parker, A. Shepon, K.D. Gorospe, K. Bergman, G. Eshel, C.D. Golden, B.S. Halpern, S. Hornborg, M. Jonell, M. Metian, K. Mifflin, R. Newton, P. Tyedmers, W. Zhang, F. Ziegler, and M. Troell, 2021: Environmental performance of blue foods. *Nature*, **597** (7876), 360–365. https://doi.org/10.1038/s41586-021-03889-2

66. Griffis, R. and J. Howard, 2013: *Oceans and Marine Resources in a Changing Climate. A Technical Input to the 2013 National Climate Assessment.* Island Press, Washington, DC, 252 pp. https://doi.org/10.5822/978-1-61091-480-2

67. Maulu, S., O.J. Hasimuna, L.H. Haambiya, C. Monde, C.G. Musuka, T.H. Makorwa, B.P. Munganga, K.J. Phiri, and J.D. Nsekanabo, 2021: Climate change effects on aquaculture production: Sustainability implications, mitigation, and adaptations. *Frontiers in Sustainable Food Systems*, **5**, 609097. https://doi.org/10.3389/fsufs.2021.609097

68. Gerwing, K. and T. McDaniels, 2006: Listening to the Salmon People: Coastal First Nations' objectives regarding salmon aquaculture in British Columbia. *Society & Natural Resources*, **19** (3), 259–273. https://doi.org/10.1080/08941920500460864

69. Naylor, R.L., J. Eagle, and W.L. Smith, 2003: Salmon aquaculture in the Pacific Northwest a global industry with local impacts. *Environment: Science and Policy for Sustainable Development*, **45** (8), 18–39. https://doi.org/10.1080/00139150309604562

70. Basche, A., K. Tully, N.L. Álvarez-Berríos, J. Reyes, L. Lengnick, T. Brown, J.M. Moore, R.E. Schattman, L.K. Johnson, and G. Roesch-McNally, 2020: Evaluating the untapped potential of US conservation investments to improve soil and environmental health. *Frontiers in Sustainable Food Systems*, **4**, 547876. https://doi.org/10.3389/fsufs.2020.547876

71. El Bilali, H., C. Callenius, C. Strassner, and L. Probst, 2019: Food and nutrition security and sustainability transitions in food systems. *Food and Energy Security*, **8** (2), e00154. https://doi.org/10.1002/fes3.154

72. Davis, K.F., S. Downs, and J.A. Gephart, 2021: Towards food supply chain resilience to environmental shocks. *Nature Food*, **2** (1), 54–65. https://doi.org/10.1038/s43016-020-00196-3

73. Godde, C.M., D. Mason-D'Croz, D.E. Mayberry, P.K. Thornton, and M. Herrero, 2021: Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, **28**, 100488. https://doi.org/10.1016/j.gfs.2020.100488

74. Jones, A.W. and A. Phillips, 2016: Historic food production shocks: Quantifying the extremes. *Sustainability*, **8** (5), 427. https://doi.org/10.3390/su8050427

75. Troy, T.J., C. Kipgen, and I. Pal, 2015: The impact of climate extremes and irrigation on US crop yields. *Environmental Research Letters*, **10** (5), 054013. https://doi.org/10.1088/1748-9326/10/5/054013

76. Vogel, E., M.G. Donat, L.V. Alexander, M. Meinshausen, D.K. Ray, D. Karoly, N. Meinshausen, and K. Frieler, 2019: The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, **14** (5), 054010. https://doi.org/10.1088/1748-9326/ab154b

77. Zampieri, M., A. Ceglar, F. Dentener, and A. Toreti, 2017: Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. *Environmental Research Letters*, **12** (6), 064008. https://doi.org/10.1088/1748-9326/aa723b

78. de Raymond, A.B., A. Alpha, T. Ben-Ari, B. Daviron, T. Nesme, and G. Tétart, 2021: Systemic risk and food security. Emerging trends and future avenues for research. *Global Food Security*, **29**, 100547. https://doi.org/10.1016/j.gfs.2021.100547

79. Dall'Erba, S., Z. Chen, and N.J. Nava, 2021: U.S. interstate trade will mitigate the negative impact of climate change on crop profit. *American Journal of Agricultural Economics*, **103** (5), 1720–1741. https://doi.org/10.1111/ajae.12204

80. Baylis, K., T. Heckelei, and T.W. Hertel, 2021: Agricultural trade and environmental sustainability. *Annual Review of Resource Economics*, **13** (1), 379–401. https://doi.org/10.1146/annurev-resource-101420-090453

81. Thilmany, D., E. Canales, S.A. Low, and K. Boys, 2021: Local food supply chain dynamics and resilience during COVID-19. *Applied Economic Perspectives and Policy*, **43** (1), 86–104. https://doi.org/10.1002/aepp.13121

82. Mbow, C., C. Rosenzweig, L.G. Barioni, T.G. Benton, M. Herrero, M. Krishnapillai, E. Liwenga, P. Pradhan, M.G. Rivera-Ferre, T. Sapkota, F.N. Tubiello, and Y. Xu, 2019: Ch. 5. Food security. In: *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Shukla, P.R., J. Skea, E.C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 437–550. https://doi.org/10.1017/9781009157988.007

83. Reardon, T. and D. Zilberman, 2018: Ch. 15. Climate smart food supply chains in developing countries in an era of rapid dual change in agrifood systems and the climate. In: *Climate Smart Agriculture: Building Resilience to Climate Change*. Lipper, L., N. McCarthy, D. Zilberman, S. Asfaw, and G. Branca, Eds. Springer, Cham, Switzerland, 335–351. https://doi.org/10.1007/978-3-319-61194-5_15

84. Reyes, J.J. and E. Elias, 2019: Spatio-temporal variation of crop loss in the United States from 2001 to 2016. *Environmental Research Letters*, **14** (7), 074017. https://doi.org/10.1088/1748-9326/ab1ac9

85. Tack, J., K. Coble, and B. Barnett, 2018: Warming temperatures will likely induce higher premium rates and government outlays for the U.S. crop insurance program. *Agricultural Economics*, **49** (5), 635–647. https://doi.org/10.1111/agec.12448

86. Diffenbaugh, N.S., F.V. Davenport, and M. Burke, 2021: Historical warming has increased U.S. crop insurance losses. *Environmental Research Letters*, **16** (8), 084025. https://doi.org/10.1088/1748-9326/ac1223

87. Ortiz-Bobea, A., E. Knippenberg, and R.G. Chambers, 2018: Growing climatic sensitivity of U.S. agriculture linked to technological change and regional specialization. *Science Advances*, **4** (12), 4343. https://doi.org/10.1126/sciadv.aat4343

88. Liang, X.-Z., Y. Wu, R.G. Chambers, D.L. Schmoldt, W. Gao, C. Liu, Y.-A. Liu, C. Sun, and J.A. Kennedy, 2017: Determining climate effects on US total agricultural productivity. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (12), E2285–E2292. https://doi.org/10.1073/pnas.1615922114

89. Ortiz-Bobea, A., T.R. Ault, C.M. Carrillo, R.G. Chambers, and D.B. Lobell, 2021: Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change*, **11** (4), 306–312. https://doi.org/10.1038/s41558-021-01000-1

90. Ortiz-Bobea, A., H. Wang, C.M. Carrillo, and T.R. Ault, 2019: Unpacking the climatic drivers of US agricultural yields. *Environmental Research Letters*, **14** (6), 064003. https://doi.org/10.1088/1748-9326/ab1e75

91. Hertel, T.W. and C.Z. de Lima, 2020: Viewpoint: Climate impacts on agriculture: Searching for keys under the streetlight. *Food Policy*, **95**, 101954. https://doi.org/10.1016/j.foodpol.2020.101954

92. Licker, R., K. Dahl, and J.T. Abatzoglou, 2022: Quantifying the impact of future extreme heat on the outdoor work sector in the United States. *Elementa: Science of the Anthropocene*, **10** (1), 00048. https://doi.org/10.1525/elementa.2021.00048

93. CDC, 2008: Heat-related deaths among crop workers—United States, 1992–2006. *Morbidity and Mortality Weekly Report*, **57** (24), 649–653. https://www.cdc.gov/mmwr/preview/mmwrhtml/mm5724a1.htm

94. Tigchelaar, M., D.S. Battisti, and J.T. Spector, 2020: Work adaptations insufficient to address growing heat risk for U.S. agricultural workers. *Environmental Research Letters*, **15** (9), 094035. https://doi.org/10.1088/1748-9326/ab86f4

95. de Lima, C.Z., J.R. Buzan, F.C. Moore, U.L.C. Baldos, M. Huber, and T.W. Hertel, 2021: Heat stress on agricultural workers exacerbates crop impacts of climate change. *Environmental Research Letters*, **16** (4), 044020. https://doi.org/10.1088/1748-9326/abeb9f

96. Al-Bazz, S.A., D. Béland, G.L. Lane, R.R. Engler-Stringer, J. White, and H. Vatanparast, 2022: Food security of temporary foreign farm workers under the seasonal agricultural worker program in Canada and the United States: A scoping review. *Advances in Nutrition*, **13** (5), 1603–1627. https://doi.org/10.1093/advances/nmac027

97. Greene, C., 2018: Broadening understandings of drought—The climate vulnerability of farmworkers and rural communities in California (USA). *Environmental Science & Policy*, **89**, 283–291. https://doi.org/10.1016/j.envsci.2018.08.002

98. Baker, J.S., P. Havlík, R. Beach, D. Leclère, E. Schmid, H. Valin, J. Cole, J. Creason, S. Ohrel, and J. McFarland, 2018: Evaluating the effects of climate change on US agricultural systems: Sensitivity to regional impact and trade expansion scenarios. *Environmental Research Letters*, **13** (6), 064019. https://doi.org/10.1088/1748-9326/aac1c2

99. Beach, R.H., Y. Cai, A. Thomson, X. Zhang, R. Jones, B.A. McCarl, A. Crimmins, J. Martinich, J. Cole, S. Ohrel, B. DeAngelo, J. McFarland, K. Strzepek, and B. Boehlert, 2015: Climate change impacts on US agriculture and forestry: Benefits of global climate stabilization. *Environmental Research Letters*, **10** (9), 095004. https://doi.org/10.1088/1748-9326/10/9/095004

100. Chodur, G.M., X. Zhao, E. Biehl, J. Mitrani-Reiser, and R. Neff, 2018: Assessing food system vulnerabilities: A fault tree modeling approach. *BMC Public Health*, **18** (1), 817. https://doi.org/10.1186/s12889-018-5563-x

101. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

102. Young, S.K. and H. Stewart, 2022: U.S. fruit and vegetable affordability on the Thrifty Food Plan depends on purchasing power and safety net supports. *International Journal of Environmental Research and Public Health*, **19** (5). https://doi.org/10.3390/ijerph19052772

103. Darmon, N. and A. Drewnowski, 2015: Contribution of food prices and diet cost to socioeconomic disparities in diet quality and health: A systematic review and analysis. *Nutrition Reviews*, **73** (10), 643–660. https://doi.org/10.1093/nutrit/nuv027

104. Koch, C.A., P. Sharda, J. Patel, S. Gubbi, R. Bansal, and M.J. Bartel, 2021: Climate change and obesity. *Hormone and Metabolic Research*, **53** (9), 575–587. https://doi.org/10.1055/a-1533-2861

105. Thompson, D., K.R. Johnson, K.M. Cistrunk, A. Vancil-Leap, T. Nyatta, L. Hossfeld, G. Rico Méndez, and C. Jones, 2020: Assemblage, food justice, and intersectionality in rural Mississippi: The Oktibbeha Food Policy Council. *Sociological Spectrum*, **40** (6), 381–399. https://doi.org/10.1080/02732173.2020.1801541

106. Cohen, A., 2021: The challenges of intersectionality in the lives of older adults living in rural areas with limited financial resources. *Gerontology and Geriatric Medicine*, **7**, 23337214211009363. https://doi.org/10.1177/23337214211009363

107. Rhoades, J.L., J.S. Gruber, and B. Horton, 2018: Developing an in-depth understanding of elderly adult's vulnerability to climate change. *The Gerontologist*, **58** (3), 567–577. https://doi.org/10.1093/geront/gnw167

108. Kindle, A., 2021: A Hunter's & Angler's Guide to Climate Change: Challenges, Opportunities & Solutions. National Wildlife Federation. https://azwildlife.org/resources/Documents/10-05-21_NWF_Outdoors%20_Climate_Report.pdf

109. Niles, M.T., K.B. Wirkkala, E.H. Belarmino, and F. Bertmann, 2021: Home food procurement impacts food security and diet quality during COVID-19. *BMC Public Health*, **21** (1), 945. https://doi.org/10.1186/s12889-021-10960-0

110. Smith, E., S. Ahmed, V. Dupuis, M. Running Crane, M. Eggers, M. Pierre, K. Flagg, and C. Byker Shanks, 2019: Contribution of wild foods to diet, food security, and cultural values amidst climate change. *Journal of Agriculture, Food Systems, and Community Development*, **9** (B), 191–214. https://doi.org/10.5304/jafscd.2019.09b.011

111. Norton-Smith, K., K. Lynn, K. Chief, K. Cozzetto, J. Donatuto, M.H. Redsteer, L.E. Kruger, J. Maldonado, C. Viles, and K.P. Whyte, 2016: Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences. Gen. Tech. Rep. PNW-GTR-944. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 136 pp. https://www.fs.usda.gov/treesearch/pubs/53156

112. Morton, J.F., 2007: The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **104** (50), 19680–19685. https://doi.org/10.1073/pnas.0701855104

113. Rodríguez-Cruz, L.A., M. Moore, and M.T. Niles, 2021: Puerto Rican farmers' obstacles toward recovery and adaptation strategies after Hurricane Maria: A mixed-methods approach to understanding adaptive capacity. *Frontiers in Sustainable Food Systems*, **5**, 662918. https://doi.org/10.3389/fsufs.2021.662918

114. Lovell, S.T., J. Hayman, H. Hemmelgarn, A.A. Hunter, and J.R. Taylor, 2021: Community orchards for food sovereignty, human health, and climate resilience: Indigenous roots and contemporary applications. *Forests*, **12** (11), 1533. https://doi.org/10.3390/f12111533

115. ERS, 2016: American Diet Includes Many High-Value Imported Products. U.S. Department of Agriculture, Economic Research Service, accessed February 21 2022. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartid=58398

116. ERS, 2019: Nearly Two-Thirds of U.S. Agricultural Imports Consist of Horticultural and Tropical Products. U.S. Department of Agriculture, Economic Research Service, accessed February 21 2022. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartid=58362

117. Lin, X., P.J. Ruess, L. Marston, and M. Konar, 2019: Food flows between counties in the United States. *Environmental Research Letters*, **14** (8), 084011. https://doi.org/10.1088/1748-9326/ab29ae

118. Crippa, M., E. Solazzo, D. Guizzardi, F. Monforti-Ferrario, F.N. Tubiello, and A. Leip, 2021: Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, **2** (3), 198–209. https://doi.org/10.1038/s43016-021-00225-9

119. EPA, 2021: From Farm to Kitchen: The Environmental Impacts of U.S. Food Waste. EPA 600-R21 171. U.S. Environmental Protection Agency, Office of Research and Development. https://www.epa.gov/land-research/farm-kitchen-environmental-impacts-us-food-waste

120. Read, Q.D., S. Brown, A.D. Cuéllar, S.M. Finn, J.A. Gephart, L.T. Marston, E. Meyer, K.A. Weitz, and M.K. Muth, 2020: Assessing the environmental impacts of halving food loss and waste along the food supply chain. *Science of The Total Environment*, **712**, 136255. https://doi.org/10.1016/j.scitotenv.2019.136255

121. Cromartie, J., 2022: Population & Migration. U.S. Department of Agriculture, Economic Research Service, accessed May 19, 2022. https://www.ers.usda.gov/topics/rural-economy-population/population-migration/

122. FRB of St. Louis, 2021: *Investing in Rural Prosperity*. Dumont, A. and D.P. Davis, Eds. Federal Reserve Bank of St. Louis. https://www.stlouisfed.org/community-development/publications/invest-in-rural

123. Cutter, S.L., K.D. Ash, and C.T. Emrich, 2016: Urban–rural differences in disaster resilience. *Annals of the American Association of Geographers*, **106** (6), 1236–1252. https://doi.org/10.1080/24694452.2016.1194740

124. Jerch, R., M.E. Kahn, and G.C. Lin, 2020: Local Public Finance Dynamics and Hurricane Shocks. Working Paper 28050. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w28050

125. Liao, Y. and C. Kousky, 2022: The fiscal impacts of wildfires on California municipalities. *Journal of the Association of Environmental and Resource Economists*, **9** (3), 455–493. https://doi.org/10.1086/717492

126. Fannin, J.M., 2018: Ch. 15. Financial resilience of local governments impacted by natural disasters: A framework for calculating climate change risk and liability. In: *Addressing Climate Change at the Community Level in the United States*. Lachapelle, P.R. and D.E. Albrecht, Eds. Routledge, 232–242. https://doi.org/10.4324/9781351211727

127. Jensen, J.K., 2009: Climate Change and Rural Communities in the U.S. Rural Policy Research Institute, 13 pp. https://rupri.org/wp-content/uploads/Climate_Change_Brief.pdf

128. FEMA, 2020: National Risk Index: Primer. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_national-risk-index_primer.pdf

129. Yabe, T., P.S.C. Rao, S.V. Ukkusuri, and S.L. Cutter, 2022: Toward data-driven, dynamical complex systems approaches to disaster resilience. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (8), e2111997119. https://doi.org/10.1073/pnas.2111997119

130. Cain, C., 2021: Ch. 33. Developing climatic capacity in rural places. In: *Investing In Rural Prosperity*. Dumont, A. and D.P. Davis, Eds. Federal Reserve Bank of St. Louis, 475–486. https://www.stlouisfed.org/-/media/project/frbstl/stlouisfed/files/pdfs/community-development/investing-rural/chapters/chapter33.pdf

131. Cutter, S.L., K.D. Ash, and C.T. Emrich, 2014: The geographies of community disaster resilience. *Global Environmental Change*, **29**, 65–77. https://doi.org/10.1016/j.gloenvcha.2014.08.005

132. Cheung, W.W.L. and T.L. Frölicher, 2020: Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. *Scientific Reports*, **10** (1), 6678. https://doi.org/10.1038/s41598-020-63650-z

133. NMFS, 2022: Fishery Disaster Determinations. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, accessed May 19, 2022. https://www.fisheries.noaa.gov/national/funding-and-financial-services/fishery-disaster-determinations

134. Peterson Williams, M.J., B. Robbins Gisclair, E. Cerny-Chipman, M. LeVine, and T. Peterson, 2022: The heat is on: Gulf of Alaska Pacific cod and climate-ready fisheries. *ICES Journal of Marine Science*, **79** (2), 573–583. https://doi.org/10.1093/icesjms/fsab032

135. McIlgorm, A., S. Hanna, G. Knapp, P. Le Floc'H, F. Millerd, and M. Pan, 2010: How will climate change alter fishery governance□ Insights from seven international case studies. *Marine Policy*, **34** (1), 170–177. https://doi.org/10.1016/j.marpol.2009.06.004

136. Szymkowiak, M. and S. Kasperski, 2021: Sustaining an Alaska coastal community: Integrating place based well-being indicators and fisheries participation. *Coastal Management*, **49** (1), 107–131. https://doi.org/10.1080/08920753.2021.1846165

137. Leibensperger, C., P. Yang, Q. Zhao, S. Wei, and X. Cai, 2021: The synergy between stakeholders for cellulosic biofuel development: Perspectives, opportunities, and barriers. *Renewable and Sustainable Energy Reviews*, **137**, 110613. https://doi.org/10.1016/j.rser.2020.110613

138. Proctor, K.W., G.S. Murthy, and C.W. Higgins, 2021: Agrivoltaics align with Green New Deal goals while supporting investment in the US' rural economy. *Sustainability*, **13** (1), 137. https://doi.org/10.3390/su13010137

139. Briske, D.D., J.P. Ritten, A.R. Campbell, T. Klemm, and A.E.H. King, 2021: Future climate variability will challenge rangeland beef cattle production in the Great Plains. *Rangelands*, **43** (1), 29–36. https://doi.org/10.1016/j.rala.2020.11.001

140. Franzluebbers, A.J. and M.H. Poore, 2021: Tall fescue management and environmental influences on soil, surface residue, and forage properties. *Agronomy Journal*, **113** (2), 2029–2043. https://doi.org/10.1002/agj2.20577

141. Nouri, A., D.C. Yoder, M. Raji, S. Ceylan, S. Jagadamma, J. Lee, F.R. Walker, X. Yin, J. Fitzpatrick, B. Trexler, P. Arelli, and A.M. Saxton, 2021: Conservation agriculture increases the soil resilience and cotton yield stability in climate extremes of the southeast US. *Communications Earth & Environment*, **2** (1), 155. https://doi.org/10.1038/s43247-021-00223-6

142. ERS. 2022: Annual Cash Receipts by Commodity. U.S. Department of Agriculture, Economic Research Service. https://data.ers.usda.gov/reports.aspx?id=17832

143. Dayer, A.A., S.H. Lutter, K.A. Sesser, C.M. Hickey, and T. Gardali, 2018: Private landowner conservation behavior following participation in voluntary incentive programs: Recommendations to facilitate behavioral persistence. *Conservation Letters*, **11** (2), e12394. https://doi.org/10.1111/conl.12394

144. Prokopy, L.S., K. Floress, J.G. Arbuckle, S.P. Church, F.R. Eanes, Y. Gao, B.M. Gramig, P. Ranjan, and A.S. Singh, 2019: Adoption of agricultural conservation practices in the United States: Evidence from 35 years of quantitative literature. *Journal of Soil and Water Conservation*, **74** (5), 520. https://doi.org/10.2489/jswc.74.5.520

145. Prokopy, L.S., K. Floress, D. Klotthor-Weinkauf, and A. Baumgart-Getz, 2008: Determinants of agricultural best management practice adoption: Evidence from the literature. *Journal of Soil and Water Conservation*, **63** (5), 300. https://doi.org/10.2489/jswc.63.5.300

146. Ranjan, P., S.P. Church, K. Floress, and L.S. Prokopy, 2019: Synthesizing conservation motivations and barriers: What have we learned from qualitative studies of farmers' behaviors in the United States? *Society & Natural Resources*, **32** (11), 1171–1199. https://doi.org/10.1080/08941920.2019.1648710

147. Conant, R.T., C.E.P. Cerri, B.B. Osborne, and K. Paustian, 2017: Grassland management impacts on soil carbon stocks: A new synthesis. *Ecological Applications*, **27** (2), 662–668. https://doi.org/10.1002/eap.1473

148. Franzluebbers, A.J., 2010: Achieving soil organic carbon sequestration with conservation agricultural systems in the southeastern United States. *Soil Science Society of America Journal*, **74** (2), 347–357. https://doi.org/10.2136/sssaj2009.0079

149. Rizzo, G., J.P. Monzon, F.A. Tenorio, R. Howard, K.G. Cassman, and P. Grassini, 2022: Climate and agronomy, not genetics, underpin recent maize yield gains in favorable environments. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (4), e2113629119. https://doi.org/10.1073/pnas.2113629119

150. Snyder, C.S., T.W. Bruulsema, T.L. Jensen, and P.E. Fixen, 2009: Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture, Ecosystems & Environment*, **133** (3), 247–266. https://doi.org/10.1016/j.agee.2009.04.021

151. Aubert, B.A., A. Schroeder, and J. Grimaudo, 2012: IT as enabler of sustainable farming: An empirical analysis of farmers' adoption decision of precision agriculture technology. *Decision Support Systems*, **54** (1), 510–520. https://doi.org/10.1016/j.dss.2012.07.002

152. Delgado, J.A., N.M. Short, D.P. Roberts, and B. Vandenberg, 2019: Big data analysis for sustainable agriculture on a geospatial cloud framework. *Frontiers in Sustainable Food Systems*, **3**, 54. https://doi.org/10.3389/fsufs.2019.00054

153. Guinée, J.B., R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, R. Buonamici, T. Ekvall, and T. Rydberg, 2011: Life cycle assessment: Past, present, and future. *Environmental Science & Technology*, **45** (1), 90–96. https://doi.org/10.1021/es101316v

154. Prasad, R., A. Bhattacharyya, and Q.D. Nguyen, 2017: Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Frontiers in Microbiology*, **8**, 1014. https://doi.org/10.3389/fmicb.2017.01014

155. Howden, S.M., J.-F. Soussana, F.N. Tubiello, N. Chhetri, M. Dunlop, and H. Meinke, 2007: Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104** (50), 19691–19696. https://doi.org/10.1073/pnas.0701890104

156. Bünemann, E.K., G. Bongiorno, Z. Bai, R.E. Creamer, G. De Deyn, R. de Goede, L. Fleskens, V. Geissen, T.W. Kuyper, P. Mäder, M. Pulleman, W. Sukkel, J.W. van Groenigen, and L. Brussaard, 2018: Soil quality–A critical review. *Soil Biology and Biochemistry*, **120**, 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

157. Qiao, L., X. Wang, P. Smith, J. Fan, Y. Lu, B. Emmett, R. Li, S. Dorling, H. Chen, S. Liu, T.G. Benton, Y. Wang, Y. Ma, R. Jiang, F. Zhang, S. Piao, C. Müller, H. Yang, Y. Hao, W. Li, and M. Fan, 2022: Soil quality both increases crop production and improves resilience to climate change. *Nature Climate Change*, **12** (6), 574–580. https://doi.org/10.1038/s41558-022-01376-8

158. Institute of Medicine and National Research Council, 2015: *A Framework for Assessing Effects of the Food System*. The National Academies Press, Washington, DC, 444 pp. https://doi.org/10.17226/18846

159. Letta, M. and R.S.J. Tol, 2019: Weather, climate and total factor productivity. *Environmental and Resource Economics*, **73** (1), 283–305. https://doi.org/10.1007/s10640-018-0262-8

160. Janssens, C., P. Havlík, T. Krisztin, J. Baker, S. Frank, T. Hasegawa, D. Leclère, S. Ohrel, S. Ragnauth, E. Schmid, H. Valin, N. Van Lipzig, and M. Maertens, 2020: Global hunger and climate change adaptation through international trade. *Nature Climate Change*, **10** (9), 829–835. https://doi.org/10.1038/s41558-020-0847-4

161. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

162. Fujimori, S., T. Iizumi, T. Hasegawa, J.y. Takakura, K. Takahashi, and Y. Hijioka, 2018: Macroeconomic impacts of climate change driven by changes in crop yields. *Sustainability*, **10** (10), 3673. https://doi.org/10.3390/su10103673

163. Caro, J.C., P. Valizadeh, A. Correa, A. Silva, and S.W. Ng, 2020: Combined fiscal policies to promote healthier diets: Effects on purchases and consumer welfare. *PLoS ONE*, **15** (1), e0226731. https://doi.org/10.1371/journal.pone.0226731

164. Ali Bhuttor, Z., 2019: Agriculture & America's Rural Economy. Harvest Returns. https://www.harvestreturns.com/blog/2019/7/15/agriculture-americas-rural-economy

165. NCSL, 2020: Challenges Facing Rural Communities. National Conference of State Legislatures. https://www.ncsl.org/agriculture-and-rural-development/challenges-facing-rural-communities

166. Arjomand, S. and D. Haight, 2017: Greener Fields: Combating Climate Change by Keeping Land in Farming in New York. American Farmland Trust. https://farmlandinfo.org/publications/greener-fields-combating-climate-change-by-keeping-land-in-farming-in-new-york/

167. NALC, 2022: Conservation Programs. National Agricultural Law Center, accessed May 19, 2022. https://nationalaglawcenter.org/research-by-topic/conservation-programs/

168. Bush, H., J. Leonard, C. Metrick, and J. Wilson, 2019: Investing to Revitalize Rural America: Practical Ways to Tackle the Growing Urban/Rural Divide. Cornerstone Capital Group, 25 pp. https://www.pathstone.com/investing-to-revitalize-rural-america/

169. Coffin, A.W., F. Akhter, M.A. Drummond, and D.R. Huggins, 2022: Editorial: Rural land change and the capacity for ecosystem conservation and sustainable production in North America. *Frontiers in Environmental Science*, **10**, 850424. https://doi.org/10.3389/fenvs.2022.850424

170. Dabson, B., 2020: Equitable Recovery and Resilience in Rural America. The Aspen Institute, 17 pp. https://www.aspeninstitute.org/publications/equitable-recovery-and-resilience-in-rural-america/

171. Inungu, J.N. and M.J. Minelli, 2022: *Foundations of Rural Public Health in America*, 1st ed. Jones & Bartlett Learning, 528 pp. https://www.jblearning.com/catalog/productdetails/9781284182453

172. Johnson, K.M. and D.T. Lichter, 2019: Rural depopulation: Growth and decline processes over the past century. *Rural Sociology*, **84** (1), 3–27. https://doi.org/10.1111/ruso.12266

173. Parker, K., J.M. Horowitz, A. Brown, R. Fry, D. Cohn, and R. Igielnik, 2018: Demographic and Economic Trends in Urban, Suburban and Rural Communities. Pew Research Center. https://www.pewresearch.org/social-trends/2018/05/22/demographic-and-economic-trends-in-urban-suburban-and-rural-communities/

174. Horney, J., M. Nguyen, D. Salvesen, C. Dwyer, J. Cooper, and P. Berke, 2017: Assessing the quality of rural hazard mitigation plans in the southeastern United States. *Journal of Planning Education and Research*, **37** (1), 56–65. https://doi.org/10.1177/0739456x16628605

175. Jayawardhan, S., 2017: Vulnerability and climate change induced human displacement. *Consilience: The Journal of Sustainable Development*, **17** (1), 103–142. http://www.jstor.org/stable/26188784

176. Johnson, E., J. Bell, D. Coker, E. Hertz, N. Labarge, and G. Blake, 2018: A lifeline and social vulnerability analysis of sea level rise impacts on rural coastal communities. *Shore and Beach*, **86**, 36–44. https://asbpa.org/publications/shore-and-beach/shore-beach-vol-86-no-4-fall-2018-abstracts/

177. Shen, S., R.H. Chang, K. Kim, and M. Julian, 2022: Challenges to maintaining disaster relief supply chains in island communities: Disaster preparedness and response in Honolulu, Hawai'i. *Natural Hazards*, **114**, 1829–1855. https://doi.org/10.1007/s11069-022-05449-x

178. Abrash Walton, A., J. Marr, M.J. Cahillane, and K. Bush, 2021: Building community resilience to disasters: A review of interventions to improve and measure public health outcomes in the northeastern United States. *Sustainability*, **13** (21), 11699. https://doi.org/10.3390/su132111699

179. Gibson, A., P. Fletcher, and M.H. McSweeney-Feld, 2018: Disaster preparedness and age-friendly cities and communities: An opportunity to impact community resilience. *Innovation in Aging*, **2** (suppl_1), 46–46. https://doi.org/10.1093/geroni/igy023.172

180. Jones, B.A., 2021: Can community resilience to disaster be taught? *International Journal of Risk and Contingency Management*, **10** (4), 58–68. https://doi.org/10.4018/ijrcm.2021100105

181. Mayer, B., 2019: A review of the literature on community resilience and disaster recovery. *Current Environmental Health Reports*, **6** (3), 167–173. https://doi.org/10.1007/s40572-019-00239-3

182. Wilson, L.A., 2022: Ch. 2. Resilience and sustainability development: Lessons from climate change adaptation research. In: *Research Anthology on Environmental and Societal Impacts of Climate Change*. Information Resources Management Association, Ed. IGI Global, Hershey, PA, 17–43. https://doi.org/10.4018/978-1-6684-3686-8.ch002

183. Eisenberg, D., T. Seager, and D.L. Alderson, 2019: Rethinking resilience analytics. *Risk Analysis*, **39** (9), 1870–1884. https://doi.org/10.1111/risa.13328

184. Hong, B., B.J. Bonczak, A. Gupta, and C.E. Kontokosta, 2021: Measuring inequality in community resilience to natural disasters using large-scale mobility data. *Nature Communications*, **12** (1), 1870. https://doi.org/10.1038/s41467-021-22160-w

185. Kontokosta, C.E. and A. Malik, 2018: The resilience to emergencies and disasters index: Applying big data to benchmark and validate neighborhood resilience capacity. *Sustainable Cities and Society*, **36**, 272–285. https://doi.org/10.1016/j.scs.2017.10.025

186. Parker, E., L. Tach, and C. Robertson, 2022: Do federal place-based policies improve economic opportunity in rural communities? *RSF: The Russell Sage Foundation Journal of the Social Sciences*, **8** (4), 125. https://doi.org/10.7758/rsf.2022.8.4.06

187. Shambaugh, R. and R. Nunn, 2018: Place-Based Policies for Shared Economic Growth. The Brookings Institution. https://www.brookings.edu/multi-chapter-report/place-based-policies-for-shared-economic-growth/

188. ERS, 2022: Rural Poverty & Well-Being. U.S. Department of Agriculture, Economic Research Service, accessed May 19, 2022. https://www.ers.usda.gov/topics/rural-economy-population/rural-poverty-well-being/

189. Niccolai, A.R., S. Damaske, and J. Park, 2022: We won't be able to find jobs here: How growing up in rural America shapes decisions about work. *RSF: The Russell Sage Foundation Journal of the Social Sciences*, **8** (4), 87. https://doi.org/10.7758/rsf.2022.8.4.04

190. Sorensen, A.A., J. Freedgood, J. Dempsey, and D.M. Theobald, 2018: Farms Under Threat: The State of America's Farmland. American Farmland Trust. https://farmlandinfo.org/wp-content/uploads/sites/2/2020/05/AFT_FUT_SAF_2020final.pdf

191. Theobald, D.M., I. Leinwand, J.J. Anderson, V. Landau, and B.G. Dickson, 2019: Loss and Fragmentation of Natural Lands in the Conterminous U.S. from 2001 to 2017. Conservation Science Partners, 9 pp. https://www.csp-inc.org/public/CSP%20Disappearing%20US%20Exec%20Summary%20011819.pdf

192. Thiede, B.C., D.T. Lichter, and T. Slack, 2018: Working, but poor: The good life in rural America? *Journal of Rural Studies*, **59**, 183–193. https://doi.org/10.1016/j.jrurstud.2016.02.007

193. Clark, S., S. Harper, and B. Weber, 2022: Growing up in rural America. *RSF: The Russell Sage Foundation Journal of the Social Sciences*, **8** (3), 1. https://doi.org/10.7758/rsf.2022.8.3.01

194. HRSA, 2022: Defining Rural Population. Health Resources and Services Administration, accessed September 7, 2022. https://www.hrsa.gov/rural-health/about-us/what-is-rural

195. Goetz, S.J., M.D. Partridge, and H.M. Stephens, 2018: The economic status of rural America in the President Trump era and beyond. *Applied Economic Perspectives and Policy*, **40** (1), 97–118. https://doi.org/10.1093/aepp/ppx061

Fifth National Climate Assessment: Chapter 12

# Built Environment, Urban Systems, and Cities

# Chapter 12. Built Environment, Urban Systems, and Cities

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# Introduction

The built environment includes human-made or modified landscapes, structures, and infrastructure systems that bring together people, services, and economic activities. This chapter focuses on the built environment found in and around cities and suburbs across the country, where most Americans live and work. Cities and urban areas are also a key part of the country's culture, nature, and historical heritage. The choices that we make today in cities, suburbs, and the built environment to address climate change will affect the livelihoods, well-being, and quality of life for all Americans in the future.

Climate change has multiple and compounding effects on cities and the built environment. Cities and urban areas are notable drivers of climate change through the creation of greenhouse gas (GHG) emissions from human consumption and land-use change (KM 12.1). Attributes of the built environment also influence local and regional climates, which are further impacted by climate change. Across the country, cities face rising temperatures and sea levels, as well as changes in extreme events such as droughts, wildfires, extreme precipitation, flooding, and heatwaves (KM 12.2). Climate change is projected to have cascading effects on critical energy, transportation, communication, and supply chain systems (Chs. 5, 13, 18; Focus on Risks to Supply Chains). Climate projections also show demographic and land-use changes and uneven distribution of climate change risk (Chs. 2, 3). Urban infrastructure will be further strained by climate change unless effective GHG mitigation and climate adaptation actions are undertaken.

Many city governments are planning for short- and medium-term climate risks to protect their economies and the well-being of communities and residents (KM 12.3). These plans involve forward-looking infrastructure designs, land use and zoning, building codes, decision support tools, and services to ensure residents' quality of life. However, implementation of these actions is uneven and limited in scale and often lacks long-term vision (Chs. 31, 32), and not all city governments recognize the inequities experienced by overburdened communities. Persistent gaps in the provision of health services, housing, food, transportation, employment opportunities, and green spaces put already-overburdened communities at a greater risk of adverse climate impacts.

The recent growth in the number of local and community-led approaches points toward the potential for more inclusive planning and implementation of climate actions (KM 12.4). Still, without evidence-based strategies to evaluate climate actions, cities risk investing in infrastructures and built environment systems that lock in future urban GHG emissions, underperform or have shortened life spans, and exacerbate adverse climate risks to overburdened communities.

## Key Message 12.1

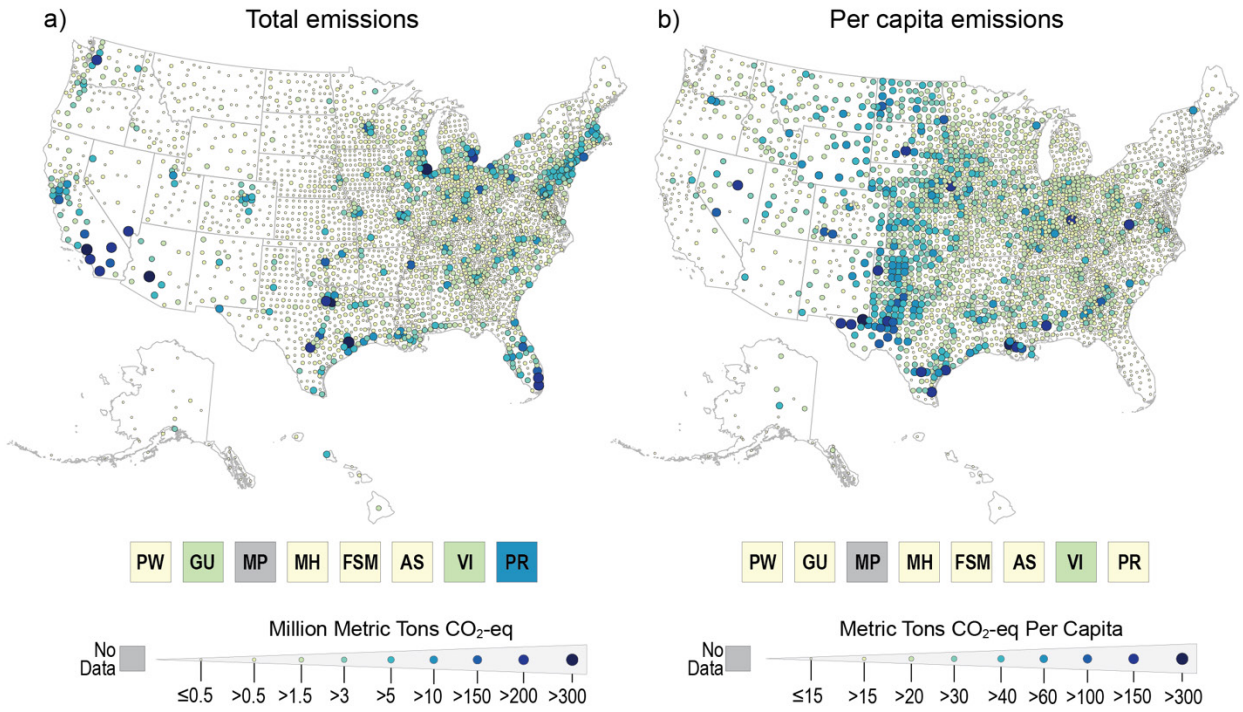
## Urban Areas Are Major Drivers of Climate Change

Consumption of food, energy, water, and materials is a major driver of global climate change, and these consumption activities are disproportionately concentrated in urban and suburban areas (*virtually certain, very high confidence*).

Human consumption and economic activity in urban and suburban areas across the country contribute a significant portion of total US GHG emissions and other air pollutants.[1,2,3] The precise proportion of emissions from urban areas depends on their definition as well as the attribution of emissions from consumption (upstream), waste (downstream), and the import and export of goods and services (indirect emissions) to urban areas.[4,5] Emissions are also unevenly distributed among cities, with the largest 10 cities plus the top 5% of suburbs accounting for more than half of all emissions in the country.[6]

Cities have large GHG emissions in absolute terms (i.e., total emissions). Approximately 70% of urban GHG emissions come from building energy consumption, fuel for transport, industry, electricity supply, and construction (Figure 12.1).[5,7,8] While high population densities in urban areas may correspond to lower per capita emissions, this metric usually does not capture the full extent of indirect emissions and consumption by urban residents as well as spatial variation within urban areas.[3,9]

## Greenhouse Gas Emissions by US County and Affiliated Territories

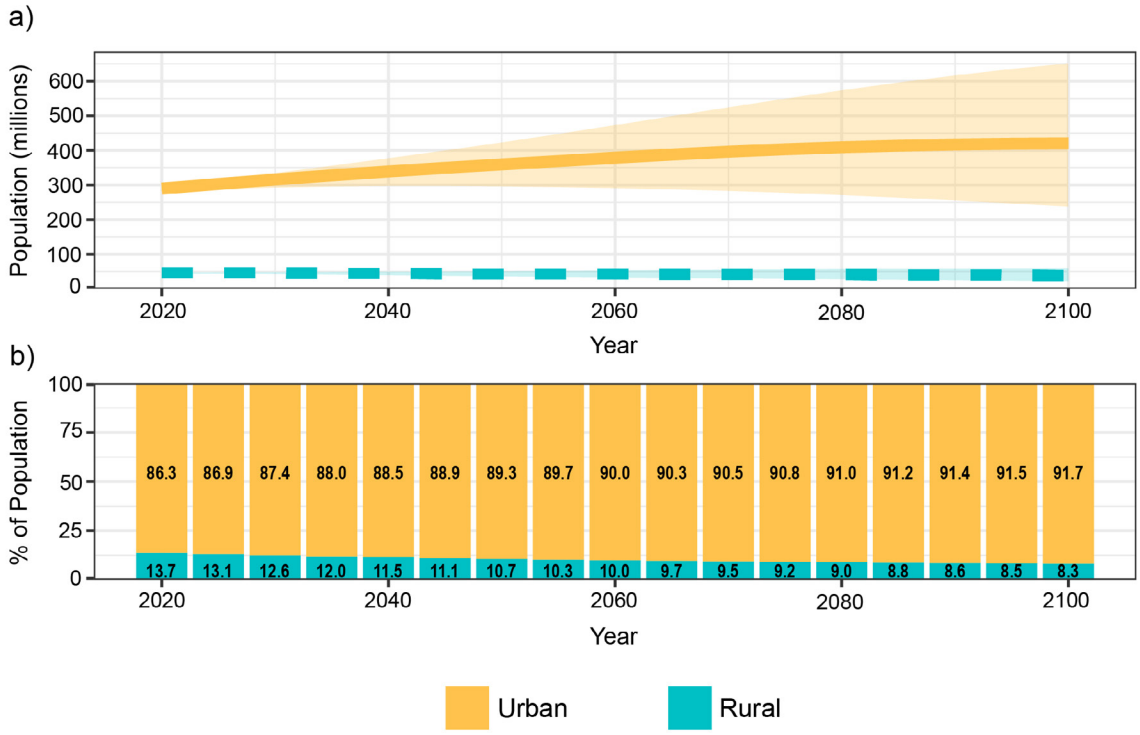



**Urban and suburban areas contribute the majority of total greenhouse gas emissions through their consumption and populations.**

**Figure 12.1.** The maps show the total (**a**) and per capita (**b**) emissions, measured in millions of metric tons of carbon dioxide equivalent ($CO_2$-eq) and metric tons of $CO_2$-eq per person, respectively. Total GHG emissions across the country are concentrated in cities and suburban areas. However, per capita emissions levels of urban and suburban residents are relatively lower compared to rural areas, although measurements usually omit indirect emissions by urban residents or the variations in their consumption levels. Emissions sources included are from electricity and natural gas used by residential, commercial, and industrial buildings, together with gasoline and diesel fuel used by on-road transportation, but do not include consumption of food, water, and materials. Data for the 50 states plus DC are by county or county equivalent for the year 2016. Data for Palau (PW), Guam (GU), Republic of the Marshall Islands (MH), Federated States of Micronesia (FSM), American Sāmoa (AS), US Virgin Islands (VI), and Puerto Rico (PR) are territory-wide—all for the year 2019 except FSM, whose data is from 2017. Commensurate data for the Northern Mariana Islands (MP) is not available. Figure credit: University of California, Davis; Northern Arizona University; NOAA NCEI; and CISESS NC.

Total emissions from urban areas may continue to grow with urban population. Figure 12.2 illustrates projected changes in US population to 2100 for urban and rural areas. Higher incomes and lower population densities relate to higher residential energy use, including transportation GHG emissions.[10,11] All of these observations indicate that if urban areas continue to grow in population, extent, and level of wealth as expected, their total emissions will also increase unless these linkages can be changed through mitigation.

## Urban and Rural Population Trends




**Urban areas constitute a significant majority of the total US population in all future scenarios.**

**Figure 12.2.** Panel (**a**) shows projected changes in urban (including suburban) and rural population in the US from 2020 to 2100 based on Shared Socioeconomic Pathways (SSPs), along with modeled scenario uncertainties in shaded areas. SSPs describe potential futures of greenhouse gas emissions and economic development, so the range of uncertainty is bounded by the overall impact of climate interventions over time. Panel (**b**) shows the proportional split between urban and rural populations based on an average SSP scenario. It shows that the proportion of urban population is expected to increase over time. Such a trend highlights the importance of reducing emissions in urban areas and the built infrastructure systems that concentrate in and around cities. Demographic data are available only for the 50 states plus DC and not available for the US Caribbean or US-Affiliated Pacific Islands. More extensive discussions of regional data availability constraints can be found in Chapters 23 and 30. Figure credit: University of California, Davis; Florida State University; Massachusetts Institute of Technology; NOAA NCEI; and CISESS NC.

## Key Message 12.2

### Attributes of the Built Environment Exacerbate Climate Impacts, Risks, and Vulnerabilities

Urban development patterns can exacerbate climate change impacts such as increases in heat and flooding (*virtually certain*, *very high confidence*). Climate change is amplifying existing loads and stressors on the built environment, and this is expected to continue (*virtually certain*, *very high confidence*). Urban areas face elevated risk as both people and the built environment are exposed to climate hazards, and these risks are distributed unevenly across the population (*virtually certain*, *very high confidence*).

Urban development patterns—resulting from past decisions about urban land use—significantly influence local and regional environments (Ch. 6), and these patterns can exacerbate the local effects of climate change. Depending on the type of built environment, both urban growth and land-use change have impacted and will continue to impact surface and ambient air temperature,[12,13,14,15,16,17] local and regional humidity,[18,19] wind patterns,[20] precipitation,[21,22,23] flooding (KM 4.1),[24,25,26] dispersion of air pollutants,[22,27] intensity of storm surges, and amount of sea level rise.[28] Figure 12.3 shows several examples of common built environment types—also termed local climate zones (LCZs)—found in cities and suburbs across the country.

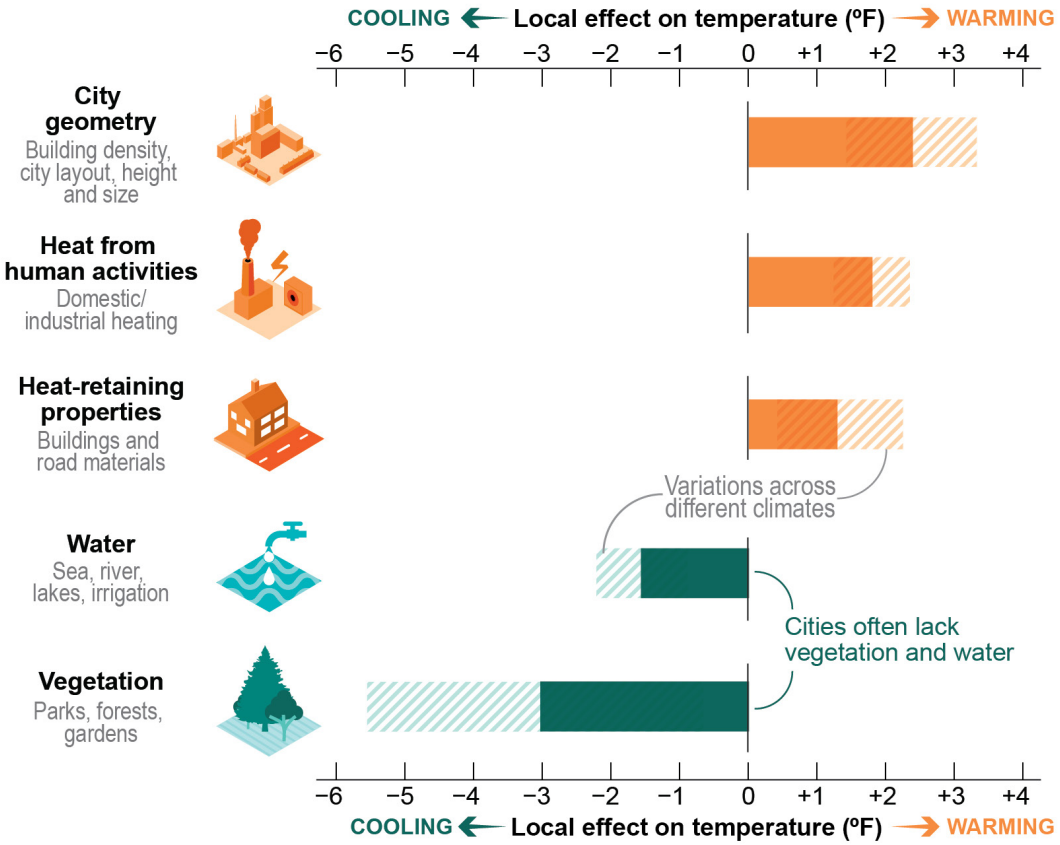
## Examples of Built Environment Types Found in US Cities

**Cities across the US include multiple types of built environments, ranging from dense urban cores to much less dense suburbs.**

**Figure 12.3.** This figure illustrates five examples of a land-use and land-cover classification scheme called local climate zones (LCZs).[29] The scheme includes 10 classes and assumes that neighborhoods of the same LCZ are similar in their ability to modify urban climate and are different from neighborhoods of other LCZs. Residents living and working in more compact neighborhoods with a high density of mid- and high-rise buildings are more likely to experience urban heat islands, as buildings retain heat and prevent ventilation. Industrial areas also see higher temperatures because of the lack of shade from tree cover and the ways dark pavement or asphalt can trap heat. The examples shown in this figure are for illustrative purposes only. Adapted from Masson et al. 2020[30] [CC BY 4.0]. Photo credits: (Seattle) july7th/E+; (Chicago) Arial_Bold/iStock; (Washington, DC) Lingbeek/E+; (Charleston) Kruck20/iStock; (Jacksonville) Art Wager/E+; (Anchorage and Tucson) Jacob Boomsma/iStock; (Salt Lake City) olaser/iStock; (Long Beach) Jorge Villalba/iStock; (Texas City) Art Wager/iStock. All photos via Getty Images.

Changes in design, form, and mass of buildings and configurations of streets, open green spaces, and water features—as well as their interactions—have direct effects on urban temperature and energy demand (Figure 12.4).[5,31,32,33] For example, average daytime land surface temperatures in Las Vegas are approximately 3.6°F (2°C) higher in areas classified as heavy industry than those classified as high-rise. Nighttime air temperatures, in particular, are expected to be higher across many urban areas due to radiant heat and heat conductance from buildings (Figure 12.5).[34,35]

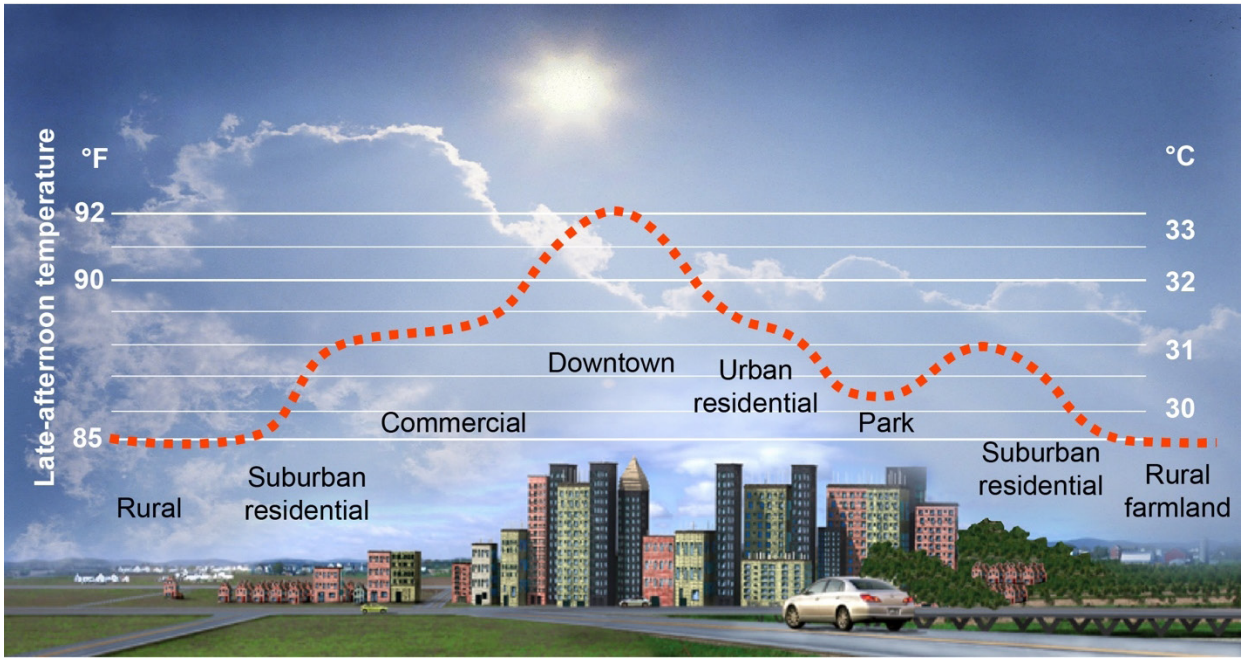
## Effects of the Built Environment on Local Temperatures




**Different aspects of the built environment affect temperatures in urban areas.**

**Figure 12.4.** Cities are often warmer than their surroundings because of the urban heat island effect—the prevalence of higher air temperatures in urban areas because of the overall density of buildings, heat absorbed and emitted by buildings and asphalt, and heat from commercial, industrial, and household activities. The hatched portions of the bars show how the effects of warming or cooling of each factor vary depending on the local climate context. For example, vegetation has a stronger cooling effect in temperate and warm climates. Adapted with permission from FAQ 10.2, Figure 1 of Doblas-Reyes et al. 2021.[36]

## The Urban Heat Island Effect




**Urban heat islands are most prominent in dense downtown areas with little access to open space.**

**Figure 12.5.** The figure illustrates temperature fluctuations across natural and built environments in a typical late afternoon in the summertime. Downtown areas with dense high-rise buildings experience the heat island effect because concrete and asphalt absorb and retain heat. Waste heat from cars, air-conditioning, and other human activities also contribute to the heat island effect. Cooler temperatures are found around urban parks, green spaces, open land, and in suburbs and rural areas. The temperature lines are shown for illustrative purposes and do not represent the climate in a particular city. Figure credit: ©Heat Island Group, Lawrence Berkeley National Laboratory. Adapted with permission.

Climate change creates negative and cascading effects on the built environment, with many infrastructure systems either projected or observed to be at risk of failing.[37,38,39,40] Temperature extremes also increase the energy demand of buildings as well as GHG emissions and air pollution.[41] Flooding overwhelms stormwater systems,[42] corrodes structures, scours foundations, and worsens indoor air quality through mold and bacteria.[43] Flooding can also inundate critical digital communication and internet infrastructure.[44,45,46] In addition, extreme heat and precipitation reduce the life expectancy of road pavements and tarmac surfaces (Ch. 13), and wildfire smoke reduces the life expectancy of heating, air-conditioning, ventilation, and filtration systems.[47]

Many infrastructure systems across the country are deteriorating and at the end of their intended useful life, and many of these are not designed to cope with additional loading due to climate change.[48,49] Climate change has significant structural implications for buildings,[50,51] as well as different risks to public, historic, and cultural assets.[52,53] Many model building codes have incorporated some hazard mitigation and climate adaptation elements; however, there remains insufficient progress in incorporating these standards at the state and local levels and in developing comprehensive architectural, design, and engineering codes and standards that enable adaptation to a wide variety of climate impacts.[48,54,55,56,57,58]

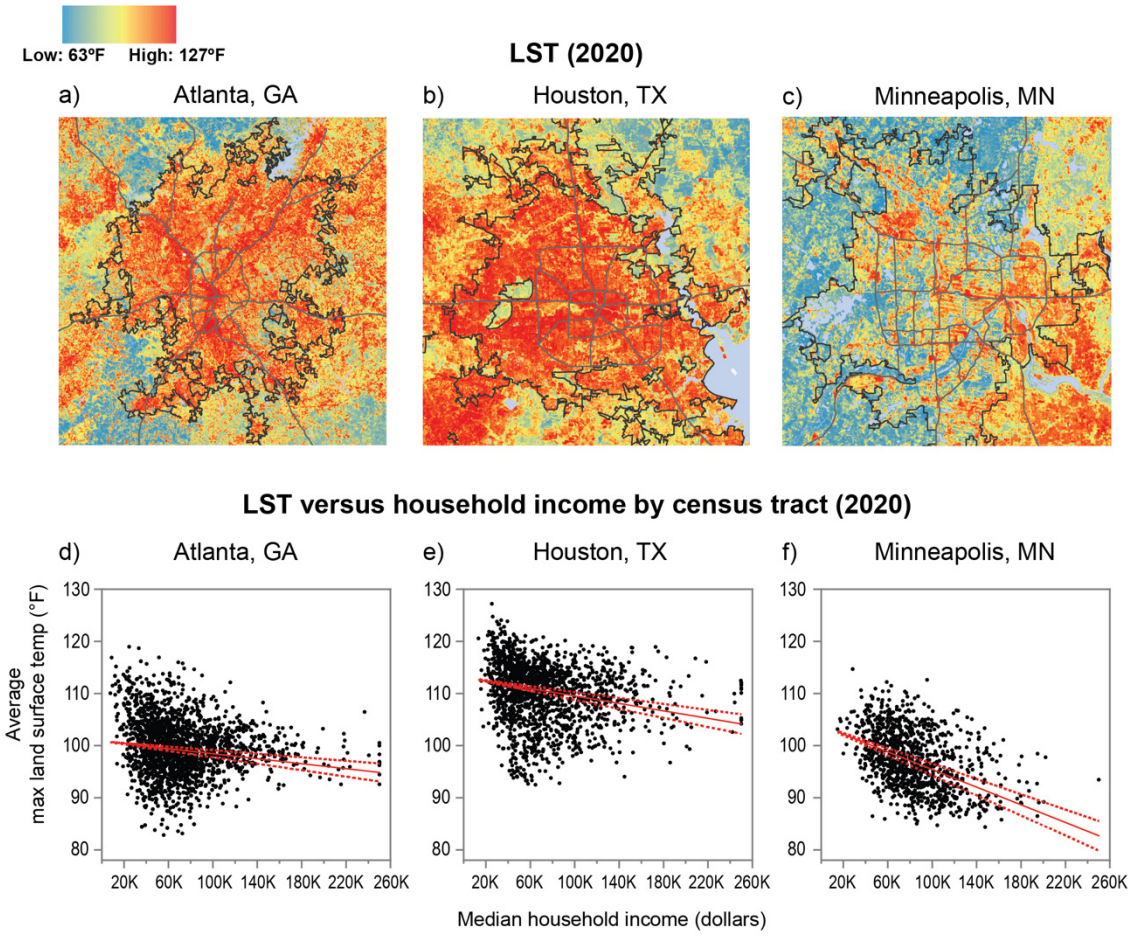
Long-term climate uncertainties will also affect future construction and maintenance of dams, levees, bridges, stormwater systems, electrical distribution systems, and building enclosures, as well as the protection of historic assets.[59,60,61,62,63] Impairment, damage, and failure across infrastructure systems are often not monitored, evaluated, or publicly disclosed within the context of climate change.[64] New stressors

such as human migration (KMs 20.3, 28.4, 30.3),[65] supply chain disruptions (Focus on Risks to Supply Chains),[66,67,68] and the COVID-19 pandemic (Focus on COVID-19 and Climate Change) all highlight the interdependent vulnerabilities of infrastructure.

Observed and anticipated climate changes disproportionately burden low-wealth communities, groups that are historically excluded from decision-making, and individuals with lower educational access (Ch. 20; KM 9.2).[69,70,71] Low-wealth neighborhoods are more exposed to heat extremes (Figure 12.6; Ch. 15),[72,73,74] where hot weather leads not only to physical discomfort for many people but also higher rates of illness and death.[75,76,77] Flood risk across the country is expected to increase disproportionately for census tracts with higher Black and Hispanic populations.[78,79] These disproportionate impacts are in part a consequence of exclusionary development practices such as redlining. Exclusionary housing practices—which persist today—leave overburdened communities with lower access to heat-reduction strategies such as urban trees and green space, as well as to broader economic and social resources.[73,80]

Another example of the uneven impact of climate change on the built environment is the deteriorating indoor air quality experienced by people living in neighborhoods with substandard housing. This includes exposure to allergens such as mold and dust [81] and pollutants such as carbon dioxide [82] and nitrogen dioxide.[83] In wildfire-prone regions, indoor air quality is additionally compromised by smoke (Ch. 28; Focus on Western Wildfires). There are also potential negative mental health outcomes from decreases in social interaction and physical activity when people are confined indoors to avoid temperature extremes.[84]

## Land Surface Temperature and Its Relationship to Median Household Income for Three Cities




**Lower-income urban neighborhoods experience higher surface temperatures.**

**Figure 12.6.** The figure shows the spatial distribution of maximum land surface temperature (LST) in 2020 for Atlanta (**a**), Houston (**b**), and Minneapolis (**c**). Graphs (**d**), (**e**), and (**f**) depict the relationship between maximum LST and median household income across census tracts in each city (see also Figure A4.4). A statistical trend analysis (the Theil-Sen estimator) returns negative values for all three cities, indicating that LST decreases as income increases (solid red line). Dashed red lines indicate the 95% confidence interval, meaning that the true slope of the trend is expected to fall within this range. Note that LST is measured at ground level and may differ from surface air temperature, which is measured at a height of 2 meters. Portions of this figure include intellectual property of Esri and its licensors and are used under license. Copyright © 2020 Esri and its licensors. All rights reserved. Figure credit: University of California, Davis; University of Texas at El Paso; Massachusetts Institute of Technology; City of Phoenix, Arizona; US Geological Survey.

Climate change impacts in urban areas are costly because of the density of infrastructure, people, and services (Ch. 19).[85,86,87] Estimates of projected annual losses vary widely based on data available and the full range of scenarios applied.[88,89,90] A more detailed assessment of the ways extreme events and climate impacts are attributed to human activities can be found in Key Messages 3.3 and 3.5. Consistent with federal guidance,[89] annual loss estimates are assessed ranging from a middle-of-the-road scenario, where GHG emissions trends do not shift markedly from historic development patterns, to a path of more rapid technical progress and increasing resource intensiveness. Quantifying annual losses according to this range can support decision-making at the local level.[90]

For urban drainage systems across the contiguous US, for example, projected average annual loss estimates range from $5 to $6.8 billion in 2090, while annual losses to electricity demand and supply systems are estimated to be $4.1–$11.2 billion in 2090 (in 2022 dollars, undiscounted).[86] For transportation infrastructure, average annual losses are estimated to range from $9.8 to $24.3 billion for roads and $620 million to $1.2 billion for bridges in 2090 (in 2022 dollars, undiscounted).[86] Costs are concentrated in the eastern half of the contiguous US due to a higher density of transportation infrastructure.[91] However, in one western state alone—Alaska—the projected annual costs of repairing, rehabilitating, or reconstructing the damage to built infrastructure from climate change could range from $100 to $207 million in 2090 (in 2022 dollars, undiscounted).[86]

Coastal counties and communities across the country are home to 123 million people (40% of total population; Ch. 9).[85,92] In the contiguous US, if no adaptation efforts are taken, estimates of average annual losses to coastal properties range from $112 to $146 billion in 2090 (in 2022 dollars, undiscounted).[86] Estimates of the value of coastal property at risk of inundation across the contiguous US range from $17 to $582 billion (in 2022 dollars, undiscounted).[85] Regions where risks to coastal properties are highest include the Southeast and Northeast Atlantic coast and Southeast Gulf coast.[85] Coastal property losses on the Southeast Atlantic coast are estimated to be nearly $692 billion per year by 2090 without adaptation (in 2022 dollars, undiscounted), with southeast Florida representing more than 80% of the total losses in the region.[91]

Homeowners, renters, stewards of cultural assets, investors, and actuaries now have greater access to information disclosing climate risks.[93,94,95] This information is critical for assessing, appraising, and managing climate risks to the built environment.[85] For example, real estate markets are responding to climate risk with adjustments to property values[96,97,98,99,100] and changes in mortgage lending practices.[94,101] Increasing awareness and belief in climate change can shape the degree to which land and property values account for climate risks.[98,102] Awareness of climate change is also associated with less housing construction in high-risk areas.[103]

## Key Message 12.3

## Urban Environments Create Opportunities for Climate Mitigation and Adaptation

Cities across the country are working to reduce greenhouse gas emissions and adapting to adverse climate impacts (*likely*, *high confidence*). Some states and cities are integrating climate considerations into relevant codes, standards, and policies. However, the pace, scale, and scope of action are not yet sufficient to avoid the worst impacts, given the magnitude of observed and projected climate changes (*virtually certain*, *very high confidence*).

The number of city-level GHG emissions-reduction and climate adaptation actions continues to grow (Figure 32.20),[104,105] although actions are concentrated among wealthier and more populous cities with resources to do more.[74,106,107,108] Federal initiatives to aid city-level efforts include the US Climate Resilience Toolkit, a guide for planning, funding, and implementing resilience efforts;[109] the National Integrated Heat Health Information System, an interagency portal for supporting communication, capacity building, and decision-making around heat;[110] funding opportunities such as FEMA's Building Resilient Infrastructure and Communities (BRIC) program; and community development block grants that consider climate risks in projects that affect low-wealth communities.

As of March 2023, 25,500 local governments and 246 Tribal governments had updated hazard mitigation and resilience plans,[111] although not all explicitly address climate risks.[112] Several hundred local jurisdictions have drafted climate action plans that specifically include GHG emissions inventories and reduction targets.[104]

City governments and residents have numerous options to lower GHG emissions and adapt to climate impacts (Table 12.1; Figures 31.1, 32.21). Urban temperature and energy demand can be reduced through physical changes in the built environment. For instance, cities can adopt or initiate certification programs to reduce building emissions, such as using the Phius standard for passive buildings[113] or the International Code Council's 2020 National Green Building Standard.[114] Cities are also using new technologies such as machine learning, remote sensing, social media, and crowdsourced initiatives to gather more climate information and reduce GHG emissions.[115,116,117,118,119,120,121]

**Table 12.1. Examples of Mitigation and Adaptation Options in Cities and Built Environments**

These examples of mitigation and adaptation options are drawn from published sources or from other NCA5 chapters. Examples are illustrative and do not represent a comprehensive list. A longer discussion of potential greenhouse gas emissions reductions by mitigation actions can be found in Chapter 32 (see Figure 32.22). Option categories are adapted from Carmin et al. 2015; IPCC 2022, 2022; and Dodman et al. 2022.[122,123,124,125]

| Societal Options | Examples |
|---|---|
| Programs and services | Climate action planning, disaster management and response, housing provision, public health services, environmental monitoring |
| Economics and finance | Social safety nets, insurance products, public finance mechanisms (such as bonds) (Box 12.1) |
| Communication and decision support | Early warning systems, hazard vulnerability assessments, health awareness training, risk assessments, civic partnerships, regional collaboratives |

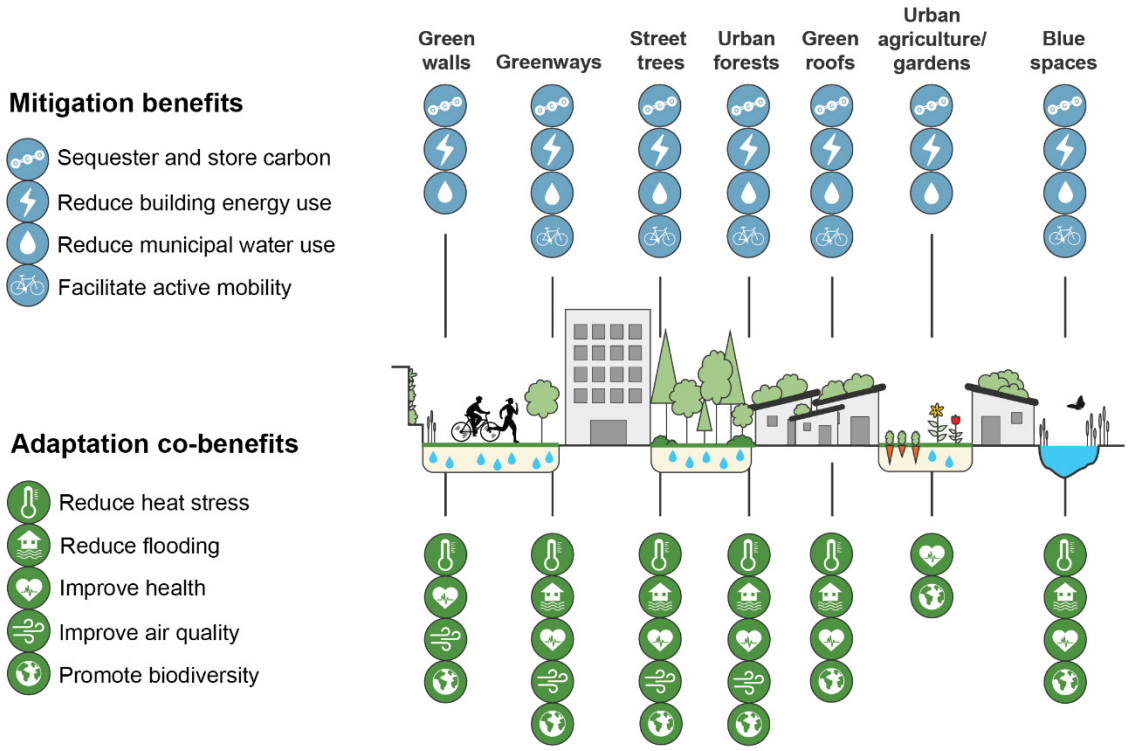
| Building Options | Examples |
|---|---|
| Energy performance | Energy-efficient building retrofits, on- and off-site renewable energy production and use,[126] community/shared solar, energy-efficient lighting and appliances, monitoring and benchmarking,[127] grid-interactive buildings (see Ch. 5) |
| Codes and standards | Building ventilation;[71] cool and evaporative roofs;[128] vegetated roofs;[129] risk-reduction standards; resilient construction materials;[130,131] electrification, energy efficiency, and other GHG emissions reductions[132] |

| Land-Use and Ecosystem Options | Examples |
|---|---|
| Gray infrastructure | High albedo/reflective pavements, coastal protection (such as seawalls), dams, flood controls, drainage (see Ch. 9) |
| Natural, green, and blue infrastructure | Urban ecosystems and biodiversity, street trees, greenery, coastal wetlands and dune systems |
| Land management | Zoning to reduce impact exposure and support GHG emissions mitigation,[133] co-location of development with low-GHG transportation and technologies,[134] reduced encroachment on natural lands, fire management, land restoration |
| Migration and relocation | Managed retreat (see Chs. 9, 16, 29, 31) |
| Resource use | Improved water supply, reduced emissions from waste and wastewater |

| Urban Transport Options | Examples |
|---|---|
| Electric/fuel-efficient vehicles | Electric vehicle charging networks,[135] purchase and operation incentives,[136,137,138] GHG and air pollution emissions standards (Ch. 13) |
| Transit, active transport | Active transport infrastructure provision (see Ch. 13), safety and comfort measures |

Many of the examples highlighted in Table 12.1 have mitigation and adaptation co-benefits.[139,140,141,142,143] Figure 12.7 illustrates select co-benefits associated with storing and sequestering carbon, preserving habitat and biodiversity, and improving water, air, and soil quality in urban areas (trade-offs are discussed in KM 12.4).

## Natural Infrastructure in Cities




**Natural infrastructure in cities provides climate mitigation and adaptation benefits.**

**Figure 12.7.** The figure illustrates the potential benefits (in no particular order) of integrating natural infrastructure strategies—also termed green, blue, or nature-based solutions—within the built environment. Nature-based, green, and blue infrastructure options are strategically planned interconnected sets of natural and constructed ecosystems, spaces with vegetation or waterscapes, and other landscape features that provide important greenhouse gas mitigation and climate adaptation functions, as well as improve human well-being, biodiversity, and ecosystem health. This figure shows examples of how urban forests and street trees can sequester and store carbon while simultaneously reducing building energy demand. Reducing municipal water use can provide a mitigation benefit by decreasing energy use in wastewater treatment plants. Adapted with permission from Figure 8.18a of Lwasa et al. 2022.[144]

Natural and nature-based solutions—of both "green" terrestrial vegetation and "blue" marine or aquatic varieties—can have GHG mitigation and climate adaptation co-benefits (Ch. 8).[13,145,146] Many nature-based solutions target extreme heat and flood hazards. Notable examples include the use of urban forestry practices to promote mature-tree shading to reduce urban heat island impacts.[74,77,147] Green roofs and green walls can reduce heat stress, increase stormwater runoff retention,[148] and lower building energy demand.[149,150,151,152] City governments and communities can draw on different green and nature-based solutions—as well as traditional "gray" interventions—ranging from urban parks to green roofs and porous pavements (Figure 12.8).[153] All of these solutions require sufficient investment in design, construction, and long-term maintenance, as well as consideration of trade-offs (e.g., water consumption for tree planting), to realize their full GHG mitigation and/or climate adaptation potential.

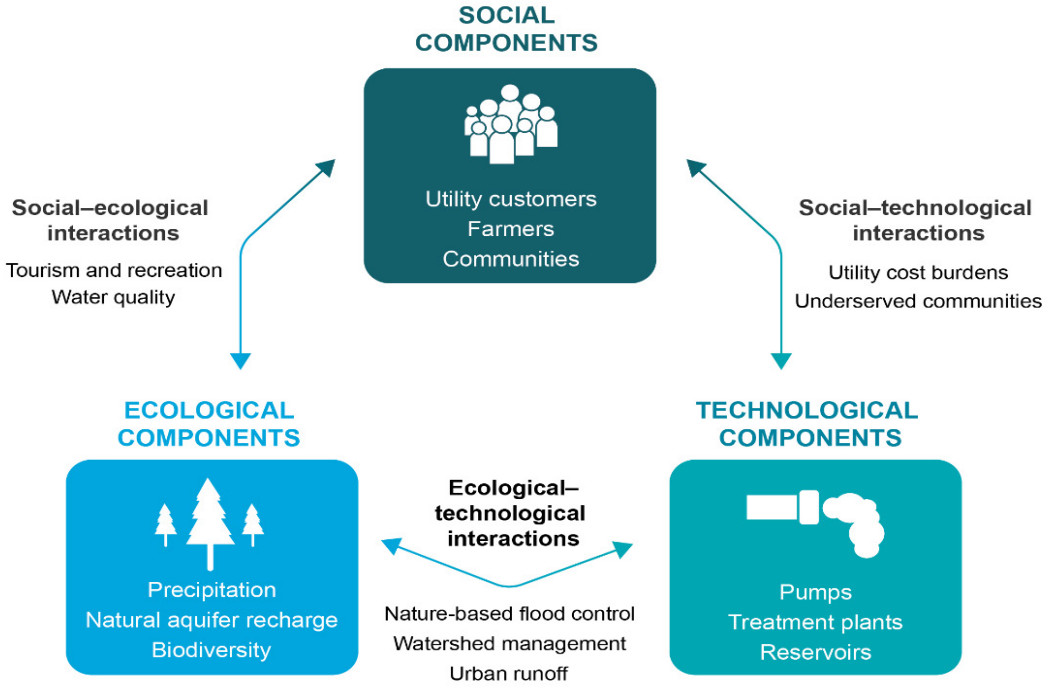
## Green, Blue, and Nature-Based Solutions

**Cities have diverse options for climate adaptation and mitigation.**

**Figure 12.8.** The figure illustrates various built environment options that consist of green, blue, and nature-based components. Examples, which are for illustrative purposes only, highlight how city governments, communities, and residents can draw on diverse options to adapt to climate impacts, reduce greenhouse gas emissions, and sequester carbon in the built environment: (**a**) remnant forest in Forest Park, Portland, Oregon; (**b**) urban agriculture in Chicago; (**c**) bioswale in Portland, Oregon; (**d**) wetlands at Bayou Bienvenue Wetland Triangle, New Orleans; (**e**) urban park in Boston; (**f**) street trees in Miami; (**g**) green roof in Arlington, Virginia; (**h**) porous pavement in Milwaukee, Wisconsin. Photo credits: (a) Ari Weil via Flickr [CC BY 2.0]; (b) Linda N. via Flickr [CC BY 2.0]; (c, d) ©Annie Marissa Matsler; (e) Kelly Sikkema via Unsplash; (f) Faith Crabtree via Unsplash; (g) Arlington County via Flickr [CC BY-SA 2.0]; (h) Aaron Volkening via Flickr [CC BY 2.0].

Forward-looking designs and governance solutions that consider joint social, ecological, and technological systems (SETS) can better anticipate and respond to future climate change (Figure 12.9).[154,155,156,157,158] Such an approach assesses the vulnerability of urban infrastructure and standardizes design methods to account for future climate risks.[159,160] This approach also highlights the need to think across ecological, social, and technological components of the built environment to provide GHG mitigation or climate adaptation benefits, in addition to equitably protecting public health, safety, and welfare[57,62,154,157] for communities that have been overburdened and underserved based on a historical lack of infrastructure investment.[161] Forward-looking designs can also prevent cities from locking in building technologies, land uses, infrastructure plans, and transportation choices based on past GHG emissions levels (Chs. 13, 32).[60]

## Social, Ecological, and Technological Components of Infrastructure




**Urban infrastructure involves joint social, ecological, and technological systems. All face risks from climate change individually and in interconnected ways.**

**Figure 12.9.** This figure is an example using water and wastewater systems to highlight the social, ecological, and technological interdependencies of infrastructure. Urban ecosystems (such as waterbodies), built infrastructure (such as pipelines and pumps), and social systems (such as residents) are impacted by climate change individually. Climate change also affects the interactions between these systems, such as when flooding overwhelms pipelines and disrupts service to utilities and/or increases utility costs for consumers. Forward-looking climate actions that consider these interactions—such as how improvements in water infrastructure affect the urban ecosystem and level of access by underserved communities—can lead to more effective and equitable outcomes. Adapted with permission from Markolf et al. 2018.[156]

Despite a growing number of actions, city governments remain slow to mitigate GHG emissions, adapt to climate impacts, and reduce the negative effects of urbanization on the local and regional climate.[74,103,104,162,163,164,165,166] Actions can be hampered by the long duration of planning and decision-making processes,[167,168] ambiguity around what counts as climate action,[165,166] financial constraints (Box 12.1), government staff turnover, difficulties with public buy-in, and gaps in knowledge and awareness.[163,169,170] These barriers constrain the ability of cities to plan for long-term and complex climate challenges (Ch. 18), such as extreme heat and drought,[171] or to effectively evaluate planning progress.[61] Smaller cities and communities generally have fewer resources and less capacity to deal with these challenges.[74,106,107,108]

To bridge these barriers, cities can pursue partnerships with governments at all levels, sectors, Tribal communities, utilities, and local residents (Table 12.2).[106,170,172] One example is the National Building Performance Standards Coalition, a nationwide group that promotes GHG emissions reduction, electrification, and social equity goals in building performance programs.[173] Some cities have appointed chief resilience officers[163] and chief heat officers.[171] Cities also develop relationships with university researchers and city-to-city networks.[107,174,175,176,177] There is growing evidence of policy diffusion and learning across cities, metropolitan regions, and states.[105,178,179,180,181,182,183]

## Box 12.1. Financing Climate Action in Local Governments

Local governments can both fund and finance climate actions.[184] Climate change also poses new fiscal risks such as declining revenues and taxes from properties and businesses located in high-risk areas.[79,162,185,186,187] While the number of financial programs, tools, and incentives has grown, structural barriers and lack of capacity remain obstacles for many cities and communities (Ch. 19).[184] External funding options are limited since most states allocate less than 1% of their operating budgets to climate actions, although some notable exceptions include New Hampshire (4.9% in 2015), Delaware (3.3% in 2015–2016), and Missouri (3.1% in 2016).[185] Some cities—such as those that are part of the Southeast Florida Regional Climate Change Compact[188]—are pooling their resources with neighboring jurisdictions, but managing these funds is challenging.[106] Many infrastructure providers also have limited ability to pass on additional costs of climate change through user fees and assessments.[189]

Cities are increasingly utilizing public and private financing models to invest in climate action.[190] Because climate investments are seen to reduce physical and policy risks, they benefit cities by improving their creditworthiness.[191,192] At the same time, a shift toward private financing models results in competing infrastructure obligations and credit constraints, which limit city governments' planning capacities.[193] For instance, overburdened and underinvested communities face increased risk exposure when markets are unwilling to finance local risk-reduction infrastructure.[194] Despite these limitations, financial markets are moving forward with mitigation and adaptation investment strategies and products across diverse asset classes, including green bonds.[195,196,197]

## Key Message 12.4

## Community-Led Actions Signal a Shift Toward Equitable Climate Governance

There is varying progress in considering who benefits from, or bears the burden of, local climate actions (*very likely*, *high confidence*). The emergence of local and community-led approaches—coupled with increasing collaboration among city, Tribal, state, and federal governments—indicates a movement toward more inclusive planning and implementation of climate actions (*likely, high confidence*).

Urban planning has made progress on including overburdened and underinvested communities, including those that have been historically excluded from decision-making. However, progress on advancing social equity and inclusion has been slow, uneven, and lacking in scale.[166,198,199,200] Approaches for evaluating the social impact of climate actions are also generally lacking (KM 31.3).[201,202,203] These gaps raise questions about not only the efficiency and effectiveness of local planning and investments but also the distribution of the cost burdens associated with climate actions.[204]

Cities are confronting difficult decisions around how to fairly and equitably distribute the benefits and burdens of GHG mitigation and climate adaptation investments and actions. Social equity and justice are important considerations when evaluating potential trade-offs between GHG mitigation, climate adaptation, and urban development. For example, floodplain restoration can reduce property damage and promote development in adjacent areas,[140,205] but it can also shift flood risks from one location to another.[206,207] If risks are shifted to burden frontline communities, low-wealth populations sometimes relocate to equally high-risk areas.[208] Similarly, urban heat planning can reduce excess heat stress and promote physical comfort in indoor and outdoor spaces by retrofitting buildings and by designing active landscapes.[165,209,210,211,212] While high-quality building retrofits can improve comfort and indoor air quality, poor-quality building retrofits that simply seal off buildings to minimize infiltration can worsen indoor air

quality by creating higher levels of trapped indoor air pollutants.[213] The health effects of indoor air pollution on building occupants pose additional risks to groups that have previously received poorer healthcare services and have lived in historically redlined neighborhoods.[214,215]

Just as with traditional gray infrastructure, the political, economic, and governance processes behind implementing green and blue infrastructure and nature-based solutions can result in social inequity and exclusion, although more research is needed to empirically measure how and how much these inequities and exclusions occur. For instance, efforts to cool streets by planting trees or creating flood barriers that also serve as parks can increase the amenity value of properties and lead to gentrification and displacement.[153,216] Climate gentrification may also arise from greater consumer demand for housing in lower-risk areas.[217] This highlights the need to address trade-offs between responding to climate change and social equity.

Pursuing inclusive and equitable climate governance can be a way to combat historic underinvestment and limited access to efficient, healthy, and affordable services and infrastructure in cities. Grassroots, community-led, and participatory actions are being documented across some cities, many of which draw on a city's civic and social infrastructure as well as residents' interest in pursuing zero-carbon, climate-resilient, and socially equitable development (Table 12.2). These actions tend to prioritize distributional strategies, such as sharing benefits and burdens more fairly, rather than inclusive efforts that recognize the needs, values, and knowledge of communities that have been historically excluded from decision-making or future generations more generally.[169,178,199,204,218,219]

**Table 12.2. Examples of Local and Community-Led Actions**

Examples of local and community-led actions are sourced from an assessment of published examples. Cities, local communities, and residents can draw on more community-led actions and forward-looking planning processes, as well as pursue collaborations with other city, Tribal, state, and federal governments. Examples are illustrative and do not represent a comprehensive list.

| Category | Examples |
|---|---|
| **Community-Led Planning and Implementation** | • Neighborhood heat action plans co-created with the community[220]<br>• Neighborhood resilience hubs that support community development and resources for emergency response[221]<br>• Virtual platforms to connect overburdened communities across the country |
| **Inclusive and Forward-Looking Urban Planning** | • Equity training for city staff and decision-makers, e.g., the US Department of Housing and Urban Development Citizen Participation and Equitable Engagement Toolkit[222]<br>• Plans with focus on youth, gender, and racial inclusion[169]<br>• Reallocation of funds to support community engagement<br>• Scenario planning,[112,223] games,[175,224] and future visioning[225] |
| **Multilevel Collaboration** | • Cross-Tribal networks[226]<br>• Collaboration with nongovernmental organizations[227]<br>• Creation of new leadership and coordinating roles[171]<br>• Expansion of public participation opportunities[169,218] |

Competing resource, capacity, and policy demands from across other local, Tribal, state, and federal entities can constrain the scope, scale, and pace of efforts to further fair and equitable GHG mitigation and climate adaptation. Such challenges could be addressed through future actions that prioritize long-term planning, new technologies, and radically different infrastructure designs, as well as through better understanding of how shifts in society and culture can help create a more socially just, inclusive, and equitable built environment.

# Traceable Accounts

## *Process Description*

Chapter 12 authors were selected according to three criteria. The first criterion was necessary disciplinary expertise as identified through the public call for comment on the Fifth National Climate Assessment (NCA5) draft prospectus—which called for social scientists, engineers, economists, architects, and urban ecologists/climate scientists—together with an initial visioning exercise by the chapter lead author based on reflections of key gaps and opportunities highlighted in NCA4. The second criterion was representation of diverse institutional affiliations, including those from the Federal Government and academia, as well as those with practitioner experience. A final criterion was recognition of diverse life and career stages, personal histories and backgrounds, and regional and geographic representation. The application of all three criteria led chapter leadership to select 11 individuals (three federal and eight academic) who encompassed early-career and senior professional stages and represented diverse disciplinary, personal, and geographical backgrounds.

The authors collected references through extensive searches on web platforms, including Scopus, Web of Science, and Google Scholar. The search focused on peer-reviewed scientific literature, working papers, and technical reports published since NCA4 to identify core areas of knowledge advancement since 2018. The literature search focused on eight topical areas: 1) urban and regional climate models and scenarios; 2) physical impacts and risks to the built environment; 3) sector-specific economic and human costs in the built environment; 4) social, ecological, and spatial vulnerabilities in the urban environment; 5) urban mitigation and adaptation options; 6) urban social equity and justice; 7) urban governance and decision-making; and 8) metrics and indicators. This led to a literature database of more than 600 sources. The author team then evaluated the sources to generate key themes and messages, which were then used to compile the four Key Message sections.

The public engagement process for Chapter 12 occurred in two phases. First, the chapter Zero Order Draft (ZOD) was publicly released through a Federal Register announcement in January 2022. The ZOD then proceeded through a six-week public commenting period. Detailed responses to these public comments were completed by the deadline of May 27, 2022. Second, the chapter ZOD went through one public engagement workshop on January 14, 2022. The workshop was attended by approximately 160 participants representing community groups, private-sector stakeholders, interested individuals, academic institutions, and nonprofits, as well as government scientists across local, state, and federal levels. The objective of the workshop was to provide participants an opportunity to exchange ideas with the author team on chapter key topics, share resources, and give feedback on issues of importance to the chapter topics.

Efforts to synthesize and assess literature were conducted in a collaborative and iterative manner, with extensive redrafting and revision efforts by all chapter authors. The approach was guided by the extensive literature database as well as chapter authors' own disciplinary expertise. The chapter team held weekly meetings throughout the drafting phase, with specific Key Message teams separately meeting nearly as frequently to discuss, draft, and revise specific sections of the chapter text. Additionally, extensive dialogues with other NCA5 chapter authors and 17 technical contributors held throughout 2022 and the spring of 2023 helped to ensure the comprehensiveness and representativeness of topics covered in the chapter.

Finally, the chapter Fourth Order Draft (4OD) went through a 12-week public review and commenting period between November 2022 and January 2023. This was accompanied by an extensive peer review conducted by the National Academies of Sciences, Engineering, and Medicine (NASEM). Detailed responses to both public and NASEM comments on the chapter 4OD were completed and approved by the chapter's review editor by April 28, 2023.

## Key Message 12.1

# Urban Areas Are Major Drivers of Climate Change

### Description of Evidence Base

The evidence base for Key Message 12.1 draws on an extensive literature—based on diverse quantitative, geospatial, remote sensing, and different modeling methodologies—assessing how land-use, economic development, and human settlement patterns have affected and will continue to affect local and regional climate processes. Recent research highlights how the consumption of food, energy, and materials in urban areas is a driver of global climate change.[1,2,3] Key Message 12.1 builds on established assessments produced in the *Second State of the Carbon Cycle Report* (SOCCR2), published in 2018. It specifically builds on Chapter 4, "Understanding Urban Carbon Fluxes," in SOCCR2[5] by highlighting the science behind the role of urban areas as primary sources (i.e., responsible for a large proportion) of greenhouse gas (GHG) emissions across North America.[6]

Key Message 12.1 draws on scientific evidence behind cities as drivers of climate change. A significant amount of research across the fields of urban ecology, energy studies, climate modeling, physical geography, and engineering shows that urban and suburban areas contribute approximately 75% of total global GHG emissions,[1] although this is distributed unequally, as the 100 largest cities account for 18% of global GHG emissions.[3] As in the literature, Key Message 12.1 categorizes GHG emissions into Scope 1, 2, or 3 emissions. Scope 1 and 2 emissions refer to direct GHG emissions associated with fuel combustion in industrial or transportation sectors and direct emissions attributed to the energy for heating and cooling, respectively.[4,5] The scientific evidence additionally illustrates various approaches to accounting for indirect emissions—that is, Scope 3 emissions—which are incurred through the purchase of goods and services, distribution of goods and services through supply chains, and waste generated in operations of built environment assets. Studies note that across all these different forms of emissions, it is necessary to think beyond the physical boundaries of urban areas.[3]

### Major Uncertainties and Research Gaps

There are uncertainties pertaining to the calculation of different sources of GHG emissions within the built environment, as well as difficulties in geographically bounding the "urban" area.[4,5] Comprehensive accounting of GHG emissions from cities and urban systems includes Scope 1, 2, and 3 emissions, but the data challenges of consistent attribution of emissions to individual cities are very high.[3,9] For example, there is evidence that cities are underreporting their own GHG emissions due to incomplete or missing data.[2] Attributing GHG emissions to cities and suburban areas requires apportioning emissions across multiple systems with multiple conceptual boundaries, including, but not limited to, spatial and territorial boundaries; useful lifetime and utilization of particular built environment systems; fixed and variable costs; ownership and decision-making; embodied emissions in material consumption and flows; and additional indirect effects and interactions between stages of use.

As in all forecasting, projecting future carbon emissions from cities and urban systems is inherently challenging because of considerable uncertainty about future trends and their interactions. Research into where and how the urban population will grow; what technologies will be available and put into use; and how people decide to build, maintain, and live within cities all depend on the interaction of future economic, social, technological, policy, and climate trends that cannot be known with complete certainty.

### Description of Confidence and Likelihood

The available recent scientific evidence documenting the role of built environment systems and urban areas as drivers of climate change is extensive (e.g., Gurney et al. 2018[5]), hence the attribution of *very high confidence*. The scientific evidence attributing GHG emissions to land-use change, economic and industrial

development, and human settlement patterns[1,2,3,12,13,14,15,16,17] is *virtually certain*. This likelihood assessment reflects a near scientific consensus that urban and suburban areas—through fossil fuel–driven industrial production, economic growth, transportation, and human consumption—contribute a majority of total global GHG emissions.

## Key Message 12.2

### Attributes of the Built Environment Exacerbate Climate Impacts, Risks, and Vulnerabilities

#### Description of Evidence Base

The evidence base for Key Message 12.2 draws on the extensive scientific literature documenting both observed and projected future natural, physical, and atmospheric trends associated with the effects of climate change on the built environment. There is broad scientific consensus that local and regional climate change in and near urban areas across the country will be affected by changes in land use, development, and human settlement patterns.[5,31,32,33] The Key Message assesses the extensive literature on impacts to surface and ambient air temperature,[12,13,14,15,16,17] local and regional humidity,[18,19] wind patterns,[20] precipitation,[21,22,23] flooding,[24,25,26] dispersion of air pollutants,[22,27] and intensity of storm surges and sea level rise.[28]

Literature from the fields of urban planning, geography, ecology, architecture, and engineering all note that the design, form, and mass of buildings and the configuration of streets and open spaces, together with their interaction, have a profound influence on urban climates.[5,31,32,33] In particular, urban systems directly add sensible heat to the environment via radiant heat and heat conductance from buildings,[35] and this is illustrated in Figures 12.4 and 12.5. There is significant research noting how extreme weather events such as landfalling hurricanes, heatwaves, and storm surges attributed to climate change have increasingly affected densely populated urban communities and their built infrastructure, as well as the ecosystems on which they depend.[20]

Key Message 12.2 assesses the scientific evidence on how climate change is posing risks to built environment systems and urban communities. Extensive evidence documents the increasing number of disasters as well as their increasing damage costs (Figure A4.5)[87] Recent scientific efforts—such as Martinich and Crimmins (2019), CBO (2019), and EPA (2021)[85,86,228]—seek to quantify the potential damages across diverse built environments, including the property and housing sectors, for projections based on multiple scenarios (e.g., RCP4.5 and RCP8.5 in the examples noted above) to the end of the 21st century. Sea level rise and increases in the frequency of hot days and extreme temperatures are key climate risks for cities documented extensively in the literature.

Key Message 12.2 also assesses US dollar estimates of projected annual damages in 2090 to different built environment sectors. Such quantitative estimates vary widely depending on the scenario applied to calculate future costs. As consistent with recent IPCC Assessment Reports and federal guidance, this chapter applies commonly used scenarios, including SSP2-4.5, which corresponds to a mid-range path of GHG emissions, and SSP5-8.5, which represents a high-end resource-intensive development path (KM 3.3).[89,229] Although there continues to be debate on the likelihood of a high-end GHG emissions scenario,[88] it is still common practice to quantify the full range of potential damages to infrastructure to support decision-making, especially for those tasked with making more near-term decisions (2050 or sooner).[90]

The Key Message assesses scientific research into the amplification of risks across built environment systems through compounding and cascading events.[37,38,39,40] As most infrastructure systems are designed for current climate conditions and are not built to withstand future climate projections, extensive evidence documents how the additional loads and stressors on infrastructure systems attributed to climate change—

especially when combined with the operational constraints of infrastructure—lead to cascading impacts across the built environment and connected systems.[39] The extensive evidence assessed in Key Message 12.2 also shows how cities and urban systems will spatially concentrate risks due to current levels of infrastructure deficits, unequal exposure of people and assets, and high levels of socioeconomic inequalities.[85,87] There is clear evidence that climate change also poses substantial financial risks to real estate assets,[230] while low-wealth communities are often less able to respond to climate change impacts or recover from exposure to extreme temperatures and natural disasters.[69,70] This Key Message responds to a larger (and growing) literature assessing climate vulnerability of urban residents,[70,215,219] particularly noting that frontline, overburdened, and low-wealth communities are often disproportionately affected by climate extremes.

Multiple emerging stressors highlight additional intersecting vulnerabilities in the urban built environment. Research has documented an increasing general awareness of climate risks by infrastructure managers, property developers, stewards of heritage sites, and urban residents.[93,94,95,100,103] This increasing awareness about climate risks is associated with less housing construction in high-risk areas. Key Message 12.2 therefore draws on the expansion in professional training, certification, guidance, assessment of existing land use, building codes and standards, risk communication, and efforts to define climate temporal and spatial resolution information needs.

## Major Uncertainties and Research Gaps

The speed, geographic distribution, and extent to which key climate stressors will change over the intended service life of the built environment is uncertain, as is the burden of these impacts on urban communities. Changes in stressors and levels of burden are already observed and documented,[37,38,39,40] but uncertainties depend on the rate of global climate change as well as regional and many local and site-specific factors, such as changes in urban population, social inequalities, and the broader economy.

It is also unknown how extensive changes in engineering design practices and management of infrastructure systems will change in response to—and in efforts to adapt to—changing climate stressors. Engineering and architectural design professionals typically focus on weather extremes,[48,54,55,56,57,58] which are projected with more uncertainty compared to changes in average conditions. Actions to account for future climate impacts depend on the ways decision-makers evaluate the costs and benefits of implementing different infrastructure designs. It is unknown how different infrastructure systems will function under changing climate conditions and what the anticipated effects on urban systems and cities will be. Another gap in understanding is whether the pace and scale of changes in architectural and engineering design practice associated with the built environment and infrastructure systems are sufficient to address the pace and scale of expected climate change impacts.

Finally, there remain gaps in understanding of the market response in locations currently exposed and sensitive to climate shocks and stressors. The extent to which US financial markets can pursue innovations that provide anticipatory investment and appraisal services within the global market is unknown. Similarly, the way in which the design and construction market can innovate to provide these services to the global market is unknown.

## Description of Confidence and Likelihood

There is scientific consensus that the increased rates of urbanization have significantly transformed the land use and land cover of cities across the US, contributing to the general degradation of the urban and regional climates.[31,32] The extensive scientific evidence evaluates how, for many urban areas, these processes will be significant and potentially dominant drivers of changes of urban climate over the remainder of this century.[34] The evidence therefore points to *very high confidence* in the role of climate change in exacerbating and amplifying loads on the built environment as well as imposing additional burdens on urban communities and infrastructure systems. There is also scientific consensus on how climate change poses

additional risks to infrastructure systems. The literature describes, in *virtually certain* terms, that cities concentrate risks given current levels of infrastructure deficits, unequal exposure of people and assets, and high levels of socioeconomic inequalities.[37,38,39,40] Climate impacts are *virtually certain* to disproportionately burden low-wealth communities, groups that have been historically excluded from decision-making, and individuals with lower educational access.[69,70,71] The extensiveness of scientific evidence supporting these observations therefore gives the third statement of this Key Message an assessment of *very high confidence*.

## Key Message 12.3

## Urban Environments Create Opportunities for Climate Mitigation and Adaptation

### Description of Evidence Base

Key Message 12.3 assesses scientific evidence of observed progress in mitigating GHG emissions and adapting to adverse climate impacts among cities across the country. Research shows that the technology or changes necessary for carbon neutrality are generally available and known to cities. Research has highlighted the growing number of cities that recognize the need to establish GHG-reduction targets; however, this research also shows that many lag behind these targets in implementation[104,105] or have broad efforts to reduce GHG emissions that tend to be similar. Since NCA4, more scientific evidence has pointed to cities planning to build resilience and adapt to climate change.[111,112] Research continues to note that efforts to enable GHG mitigation and climate adaptation, as well as efforts to realize their co-benefits remain difficult to implement.[162]

Recent scientific evidence documents how an increasing number of states and cities are considering climate risks in their relevant codes, standards, and policies, although such progress is not yet sufficient. For instance, there are emerging building standards, codes, and designs to enable forward-looking and anticipatory approaches to planning and designing for climate change across different built environment and infrastructure types.[62,154,157] Many city governments are also exploring strategies to protect infrastructure against sea level rise in the near and long term.

Example actions that are rapidly gaining popularity are nature-based solutions,[13,145,146,153] including those illustrated in Figures 12.7 and 12.8. Since NCA4, there has been a marked increase in the scientific literature documenting climate actions that utilize natural materials and processes to help protect infrastructure against different kinds of extreme risk.[146] An increasing number of quantitative, qualitative, and case study–based research has focused on nature-based solutions such as marshes, mangroves, dunes, beach nourishment, and several other types of natural structures (see Figure 12.8). Table 12.1 synthesizes some examples of GHG mitigation and climate adaptation actions in cities and the built environment that are sourced from published examples or from other NCA5 chapters.

Key Message 12.3 assesses the scientific evidence in quantifying a range of economic, health, and environmental co-benefits from mitigation and adaptation actions in cities and built environment systems.[139,141] Since NCA4, there is now a better understanding of how climate co-benefits are distributed across a community—in particular among overburdened and underserved communities—and how they can help to reduce gaps in uptake by increasing adaptive capacity while addressing historical disparities.[142,143]

### Major Uncertainties and Research Gaps

Despite recent advances in scientific research on the different ways climate change efforts are integrated into planning processes, land-use controls, building designs, and financing mechanisms, there is still a lot to learn about how people modify their activity patterns in response to weather and climate. The scientific evidence on attributing individual and collective behavior change to specific experiences of climate change

is still uncertain. Research gaps also exist in understanding specific policy changes in response to climate priorities, including the role of leadership, learning, and diffusion of ideas. Much of this research is based on single-case studies that are difficult to scale up and generalize. Of the larger-scale quantitative analyses that are available, many continue to show varying explanations. This research highlights different challenges. For example, one challenge is the definitional ambiguity regarding what counts as climate action.[163,165,166] Meerow and Keith (2022)[74] also document barriers related to human and financial resources and political will, while Barrage and Furst (2019)[103] note the prevalence of climate denialism.

### Description of Confidence and Likelihood

Extensive scientific research representing diverse disciplines reflects *high confidence* in the continued growth in the number of city-level GHG emissions mitigation and climate adaptation plans found across the country. There has also been a large increase in scientific research documenting the drivers of climate action uptake in cities, with many quantitative and qualitative studies representing diverse regions and geographies.[105,179,180,181,182,183]

Despite the growth in number of plans in recent years, the empirical evidence also shows that the implementation of mitigation and adaptation actions in cities and local governments remains behind. As such, even though there is near certainty that city-level climate plans are being drafted and released, the data show that it is only *likely* that city governments and urban residents are employing an increasing variety of tools and strategies to enable implementation on the ground. Research notes how this difference can be attributed to the reality that planning processes and implementation of efforts are context-dependent, meaning the drivers and incentives of action are tied to local political, social, economic, and ecological factors.[74,103,104,162,163,164,165,166] Therefore, given the assessment of this emerging literature, it is *virtually certain* and there is *very high confidence* that the scope, scale, and pace of actions are not enough given the magnitude of observed and projected climate impacts of built environments and urban systems.[74,103,104,162,163,164,165,166]

## Key Message 12.4

## Community-Led Actions Signal a Shift Toward Equitable Climate Governance

### Description of Evidence Base

The scientific evidence on urban climate change efforts highlights a growing concern over how their potential benefits and burdens will be borne by society.[169,178,199,204,219] In response, Key Message 12.4 assesses scientific evidence on the social equity implications of climate change planning efforts. Recently there have been increasing efforts to document the inherent inequalities in how climate actions are planned, designed, and implemented in local contexts, especially where cities across the country already see high levels of social and economic inequality.[166,169,198,199,200] More research on community-based, community-led, and bottom-up strategies has also emerged to better recognize the needs of urban frontline and overburdened communities,[178] including Black, Hispanic/Latino/Latinx, Pacific Islander, Alaska Native, and Indigenous communities,[226] as well as low-wealth groups.

Key Message 12.4 documents moderate but growing scientific evidence of inclusive planning and implementation approaches.[220,221] For some overburdened communities, the pursuit of equitable climate action can be a strategy to address historic underinvestments and to mobilize access to more healthcare and affordable urban services and infrastructure. Fiack et al. (2021)[204] find that social equity climate adaptation is present on the local level, based on 22 of 100 largest cities in the country. Many local governments are also actively collaborating with local stakeholders[106,107] for a wide variety of climate impacts, from extreme heat to sea level rise.

Table 12.2 illustrates several examples of shifts in urban climate governance toward local and community-led planning and implementation. Local governments that embed equity into their GHG mitigation and climate adaptation plans can focus on transforming process and shifting power and capacities to communities. Much scientific evidence shows that climate action plans are created and implemented when cities experience greater climate vulnerability and have active resident support and where governments have other related plans in place.[107,181] Still, a lot of scientific evidence suggests that participatory approaches remain challenging. For example, Sarzynski (2018)[218] showed how, in Baltimore, resilience has been limited to government actions and the city has had difficulty getting the community buy into their responsibility. Stults and Larsen (2020),[112] in analyzing 44 US local climate adaptation plans, found that none used local scenario planning or robust strategies.

## Major Uncertainties and Research Gaps

For Key Message 12.4, the major sources of uncertainty pertain to the specific drivers of inequality (especially in urban communities that experience housing insecurity, lower pay, and lower socioeconomic indicators) associated with the implementation of specific GHG emissions mitigation and climate adaptation actions, as well as the uncertainties surrounding the long-term social impacts of climate-driven inequalities. Although there is ample empirical research documenting how climate change decision-making processes often do not consider frontline populations, overburdened communities, Indigenous Peoples, and groups historically excluded from decision-making,[166,169,198,199,200] the literature disagrees on whether specific climate change actions directly contribute to producing more burden on particular groups, such as through displacement. There is also considerable uncertainty around whether and how growing considerations of inclusion and fairness actually lead to more just and equitable outcomes on the ground.

## Description of Confidence and Likelihood

Despite a notable shift in scientific research toward socially equitable and fair climate change actions, Key Message 12.4 notes with *high confidence* that actual progress in inclusive planning and implementation on the ground remains variable.[166,198,199,200] This assessment is based on scientific research published since NCA4 showing the increasing uptake of social equity and justice ideas in climate change plans and policies across cities and regions. Many of these plans and policies identify socioeconomic vulnerabilities and heightened risks experienced by frontline communities, but research shows that they fall short in incorporating social equity and justice priorities into the design and implementation of mitigation and adaptation efforts.[169,178,199,204,219] Some notable exceptions include larger cities or cities that have recent experience with extreme impacts, hence the assessment that implementation remains variable across the US.

Over the past several years, research in social sciences has broadly critiqued the way city-level plans have approached social equity and inclusion in climate plans. Research shows progress in documenting how climate change decision-making processes *very likely* do not include historically excluded populations, overburdened communities, and Indigenous Peoples. This research also notes the roles of civil society, nongovernmental organizations, social movements, and others in enabling more inclusive climate actions. Similarly, the literature documents an increasing number of partnerships across levels of government and between sectors to support decision-making and implementation.[106,107,169,170,171,172,174,175,176,177,218,227] With this growing body of literature, the Key Message notes with *high confidence* the growing number of participatory, community-led, and broadly inclusive decision-making arrangements found across the US, as well as how these arrangements are *likely* being considered in conjunction with traditional planning processes.

# References


1. Gurney, K.R., J. Liang, R. Patarasuk, Y. Song, J. Huang, and G. Roest, 2020: The Vulcan version 3.0 high-resolution fossil fuel $CO_2$ emissions for the United States. *Journal of Geophysical Research: Atmospheres*, **125** (19), e2020JD032974. https://doi.org/10.1029/2020jd032974

2. Gurney, K.R., J. Liang, G. Roest, Y. Song, K. Mueller, and T. Lauvaux, 2021: Under-reporting of greenhouse gas emissions in U.S. cities. *Nature Communications*, **12** (1), 553. https://doi.org/10.1038/s41467-020-20871-0

3. Seto, K.C., G. Churkina, A. Hsu, M. Keller, P.W.G. Newman, B. Qin, and A. Ramaswami, 2021: From low- to net-zero carbon cities: The next global agenda. *Annual Review of Environment and Resources*, **46** (1), 377–415. https://doi.org/10.1146/annurev-environ-050120-113117

4. de Chalendar, J.A., J. Taggart, and S.M. Benson, 2019: Tracking emissions in the US electricity system. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (51), 25497–25502. https://doi.org/10.1073/pnas.1912950116

5. Gurney, K.R., P. Romero-Lankao, S. Pincetl, M. Betsill, M. Chester, F. Creutzig, K. Davis, R. Duren, G. Franco, S. Hughes, L. R. Hutyra, C. Kennedy, R. Krueger, P. J. Marcotullio, D. Pataki, D. Sailor, and K.V.R. Schäfer, 2018: Ch. 4. Understanding urban carbon fluxes. In: *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*. Cavallaro, N., G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, and Z. Zhu, Eds. U.S. Global Change Research Program, Washington, DC, 189–228. https://doi.org/10.7930/soccr2.2018.ch4

6. Moran, D., K. Kanemoto, M. Jiborn, R. Wood, J. Többen, and K.C. Seto, 2018: Carbon footprints of 13,000 cities. *Environmental Research Letters*, **13** (6), 064041. https://doi.org/10.1088/1748-9326/aac72a

7. C40 Cities, 2018: Consumption-Based GHG Emissions of C40 Cities. C40 Cities Climate Leadership Group. https://www.c40knowledgehub.org/s/article/Consumption-based-GHG-emissions-of-C40-cities?language=en_US

8. Song, K., S. Qu, M. Taiebat, S. Liang, and M. Xu, 2019: Scale, distribution and variations of global greenhouse gas emissions driven by U.S. households. *Environment International*, **133**, 105137. https://doi.org/10.1016/j.envint.2019.105137

9. Wiedmann, T., G. Chen, A. Owen, M. Lenzen, M. Doust, J. Barrett, and K. Steele, 2021: Three-scope carbon emission inventories of global cities. *Journal of Industrial Ecology*, **25** (3), 735–750. https://doi.org/10.1111/jiec.13063

10. Goldstein, B., D. Gounaridis, and J.P. Newell, 2020: The carbon footprint of household energy use in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (32), 19122–19130. https://doi.org/10.1073/pnas.1922205117

11. Jones, C.M., S.M. Wheeler, and D.M. Kammen, 2018: Carbon footprint planning: Quantifying local and state mitigation opportunities for 700 California cities. *Urban Planning*, **3** (3), 35–51. https://doi.org/10.17645/up.v3i2.1218

12. Ghandehari, M., T. Emig, and M. Aghamohamadnia, 2018: Surface temperatures in New York City: Geospatial data enables the accurate prediction of radiative heat transfer. *Scientific Reports*, **8** (1), 2224. https://doi.org/10.1038/s41598-018-19846-5

13. Howe, D.A., J.M. Hathaway, K.N. Ellis, and L.R. Mason, 2017: Spatial and temporal variability of air temperature across urban neighborhoods with varying amounts of tree canopy. *Urban Forestry & Urban Greening*, **27**, 109–116. https://doi.org/10.1016/j.ufug.2017.07.001

14. Kim, S.W. and R.D. Brown, 2021: Urban heat island (UHI) variations within a city boundary: A systematic literature review. *Renewable and Sustainable Energy Reviews*, **148**, 111256. https://doi.org/10.1016/j.rser.2021.111256

15. Parida, B.R., S. Bar, D. Kaskaoutis, A.C. Pandey, S.D. Polade, and S. Goswami, 2021: Impact of COVID-19 induced lockdown on land surface temperature, aerosol, and urban heat in Europe and North America. *Sustainable Cities and Society*, **75**, 103336. https://doi.org/10.1016/j.scs.2021.103336

16. Tsoka, S., K. Tsikaloudaki, T. Theodosiou, and D. Bikas, 2020: Urban warming and cities' microclimates: Investigation methods and mitigation strategies—A review. *Energies*, **13** (6), 1414. https://doi.org/10.3390/en13061414

17. Wimberly, M.C., J.K. Davis, M.V. Evans, A. Hess, P.M. Newberry, N. Solano-Asamoah, and C.C. Murdock, 2020: Land cover affects microclimate and temperature suitability for arbovirus transmission in an urban landscape. *PLoS Neglected Tropical Diseases*, **14** (9), e0008614. https://doi.org/10.1371/journal.pntd.0008614

18. Crum, S.M. and G.D. Jenerette, 2017: Microclimate variation among urban land covers: The importance of vertical and horizontal structure in air and land surface temperature relationships. *Journal of Applied Meteorology and Climatology*, **56** (9), 2531–2543. https://doi.org/10.1175/jamc-d-17-0054.1

19. Sarangi, C., Y. Qian, J. Li, L.R. Leung, T.C. Chakraborty, and Y. Liu, 2021: Urbanization amplifies nighttime heat stress on warmer days over the US. *Geophysical Research Letters*, **48** (24), e2021GL095678. https://doi.org/10.1029/2021gl095678

20. Cao, Q., Y. Liu, M. Georgescu, and J. Wu, 2020: Impacts of landscape changes on local and regional climate: A systematic review. *Landscape Ecology*, **35** (6), 1269–1290. https://doi.org/10.1007/s10980-020-01015-7

21. Liu, J. and D. Niyogi, 2020: Identification of linkages between urban heat Island magnitude and urban rainfall modification by use of causal discovery algorithms. *Urban Climate*, **33**, 100659. https://doi.org/10.1016/j.uclim.2020.100659

22. Schmid, P.E. and D. Niyogi, 2017: Modeling urban precipitation modification by spatially heterogeneous aerosols. *Journal of Applied Meteorology and Climatology*, **56** (8), 2141–2153. https://doi.org/10.1175/jamc-d-16-0320.1

23. Shepherd, J.M., S.J. Burian, M. Jin, C. Liu, and B. Johnson, 2020: Ch. 29. Two decades of urban hydroclimatological studies have yielded discovery and societal benefits. In: *Satellite Precipitation Measurement. Advances in Global Change Research*. Levizzani, V., C. Kidd, D.B. Kirschbaum, C.D. Kummerow, K. Nakamura, and F.J. Turk, Eds. Springer, Cham, Switzerland, 1055–1072. https://doi.org/10.1007/978-3-030-35798-6_29

24. Hodgkins, G.A., R.W. Dudley, S.A. Archfield, and B. Renard, 2019: Effects of climate, regulation, and urbanization on historical flood trends in the United States. *Journal of Hydrology*, **573**, 697–709. https://doi.org/10.1016/j.jhydrol.2019.03.102

25. Jacobs, J.M., L.R. Cattaneo, W. Sweet, and T. Mansfield, 2018: Recent and future outlooks for nuisance flooding impacts on roadways on the U.S. East Coast. *Transportation Research Record*, **2672** (2), 1–10. https://doi.org/10.1177/0361198118756366

26. Wing, O.E.J., P.D. Bates, A.M. Smith, C.C. Sampson, K.A. Johnson, J. Fargione, and P. Morefield, 2018: Estimates of present and future flood risk in the conterminous United States. *Environmental Research Letters*, **13** (3), 034023. https://doi.org/10.1088/1748-9326/aaac65

27. Jiang, Z., B.C. McDonald, H. Worden, J.R. Worden, K. Miyazaki, Z. Qu, D.K. Henze, D.B.A. Jones, A.F. Arellano, E.V. Fischer, L. Zhu, and K.F. Boersma, 2018: Unexpected slowdown of US pollutant emission reduction in the past decade. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (20), 5099–5104. https://doi.org/10.1073/pnas.1801191115

28. Song, X.-P., M.C. Hansen, S.V. Stehman, P.V. Potapov, A. Tyukavina, E.F. Vermote, and J.R. Townshend, 2018: Global land change from 1982 to 2016. *Nature*, **560** (7720), 639–643. https://doi.org/10.1038/s41586-018-0411-9

29. Stewart, I.D. and T.R. Oke, 2012: Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society*, **93** (12), 1879–1900. https://doi.org/10.1175/bams-d-11-00019.1

30. Masson, V., A. Lemonsu, J. Hidalgo, and J. Voogt, 2020: Urban climates and climate change. *Annual Review of Environment and Resources*, **45** (1), 411–444. https://doi.org/10.1146/annurev-environ-012320-083623

31. IPCC, 2018: *Global Warming of 1.5°C. an IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts To Eradicate Poverty*. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157940

32. Qian, Y., T.C. Chakraborty, J. Li, D. Li, C. He, C. Sarangi, F. Chen, X. Yang, and L.R. Leung, 2022: Urbanization impact on regional climate and extreme weather: Current understanding, uncertainties, and future research directions. *Advances in Atmospheric Sciences*, **39** (6), 819–860. https://doi.org/10.1007/s00376-021-1371-9

33. Webb, B., 2017: The use of urban climatology in local climate change strategies: A comparative perspective. *International Planning Studies*, **22** (2), 68–84. https://doi.org/10.1080/13563475.2016.1169916

34. Georgescu, M., P.E. Morefield, B.G. Bierwagen, and C.P. Weaver, 2014: Urban adaptation can roll back warming of emerging megapolitan regions. *Proceedings of the National Academy of Sciences of the United States of America*, **111** (8), 2909–2914. https://doi.org/10.1073/pnas.1322280111

35. Oke, T.R., G. Mills, A. Christen, and J.A. Voogt, 2017: *Urban Climates*. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/9781139016476

36. Doblas-Reyes, F.J., A.A. Sörensson, M. Almazroui, A. Dosio, W.J. Gutowski, R. Haarsma, R. Hamdi, B. Hewitson, W.-T. Kwon, B.L. Lamptey, D. Maraun, T.S. Stephenson, I. Takayabu, L. Terray, A. Turner, and Z. Zuo, 2021: Ch. 10. Linking global to regional climate change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1363–1512. https://doi.org/10.1017/9781009157896.012

37. Clark, S.S., M.V. Chester, T.P. Seager, and D.A. Eisenberg, 2019: The vulnerability of interdependent urban infrastructure systems to climate change: Could Phoenix experience a Katrina of extreme heat? *Sustainable and Resilient Infrastructure*, **4** (1), 21–35. https://doi.org/10.1080/23789689.2018.1448668

38. Habel, S., C.H. Fletcher, T.R. Anderson, and P.R. Thompson, 2020: Sea-level rise induced multi-mechanism flooding and contribution to urban infrastructure failure. *Scientific Reports*, **10** (1), 3796. https://doi.org/10.1038/s41598-020-60762-4

39. Okour, Y., N.B. Rajkovich, and M. Bohm, 2019: Balancing adaptation and mitigation in the building sector of New York State. In: *Handbook of Climate Change Resilience*. Leal Filho, W., Ed. Springer, Cham, Switzerland, 1–17. https://doi.org/10.1007/978-3-319-71025-9_124-1

40. Stone Jr., B., E. Mallen, M. Rajput, C.J. Gronlund, A.M. Broadbent, E.S. Krayenhoff, G. Augenbroe, M.S. O'Neill, and M. Georgescu, 2021: Compound climate and infrastructure events: How electrical grid failure alters heat wave risk. *Environmental Science & Technology*, **55** (10), 6957–6964. https://doi.org/10.1021/acs.est.1c00024

41. Williams, A., L. McDonogh-Wong, and J.D. Spengler, 2020: The influence of extreme heat on police and fire department services in 23 U.S. cities. *GeoHealth*, **4** (11), e2020GH000282. https://doi.org/10.1029/2020gh000282

42. Cook, L.M., S. McGinnis, and C. Samaras, 2020: The effect of modeling choices on updating intensity-duration-frequency curves and stormwater infrastructure designs for climate change. *Climatic Change*, **159** (2), 289–308. https://doi.org/10.1007/s10584-019-02649-6

43. Rajkovich, N.B., M.E. Tuzzo, N. Heckman, K. Macy, E. Gilman, M. Bohm, and H.-R. Tanner, 2018: Climate Resilience Strategies for Buildings in New York State. Report Number 18-11. New York State Energy Research and Development Authority, Albany, NY. https://ap.buffalo.edu/content/dam/ap/PDFs/NYSERDA/Climate-Resilience-Strategies-for-Buildings.pdf

44. Argyroudis, S.A., S.A. Mitoulis, E. Chatzi, J.W. Baker, I. Brilakis, K. Gkoumas, M. Vousdoukas, W. Hynes, S. Carluccio, O. Keou, D.M. Frangopol, and I. Linkov, 2022: Digital technologies can enhance climate resilience of critical infrastructure. *Climate Risk Management*, **35**, 2212–0963. https://doi.org/10.1016/j.crm.2021.100387.

45. Balogun, A.-L., D. Marks, R. Sharma, H. Shekhar, C. Balmes, D. Maheng, A. Arshad, and P. Salehi, 2020: Assessing the potentials of digitalization as a tool for climate change adaptation and sustainable development in urban centres. *Sustainable Cities and Society*, **53**, 101888. https://doi.org/10.1016/j.scs.2019.101888

46. Durairajan, R., C. Barford, and P. Barford, 2018: Lights out: Climate change risk to Internet infrastructure. *Proceedings of the Applied Networking Research Workshop*, Montreal, QC, Canada. Association for Computing Machinery, 9–15. https://doi.org/10.1145/3232755.3232775

47. ASHRAE, 2021: Planning Framework for Protecting Commercial Building Occupants from Smoke During Wildfire Events. American Society of Heating, Refrigerating and Air-Conditioning Engineers, 17 pp. https://www.ashrae.org/File%20Library/Technical%20Resources/COVID-19/Planning-Framework-for-Protecting-Commercial-Building-Occupants-from-Smoke-During-Wildfire-Events.pdf

48. ASCE, 2021: A Comprehensive Assessment of America's Infrastructure: 2021 Report Card for America's Infrastructure. American Society of Civil Engineers. https://infrastructurereportcard.org/

49. Lopez-Cantu, T. and C. Samaras, 2018: Temporal and spatial evaluation of stormwater engineering standards reveals risks and priorities across the United States. *Environmental Research Letters*, **13** (7), 074006. https://doi.org/10.1088/1748-9326/aac696

50. Esmaeili, M. and M. Barbato, 2021: Predictive model for hurricane wind hazard under changing climate conditions. *Natural Hazards Review*, **22** (3), 04021011. https://doi.org/10.1061/(asce)nh.1527-6996.0000458

51. Pant, S. and E.J. Cha, 2019: Wind and rainfall loss assessment for residential buildings under climate-dependent hurricane scenarios. *Structure and Infrastructure Engineering*, **15** (6), 771–782. https://doi.org/10.1080/15732479.2019.1572199

52. Dawson, T., J. Hambly, A. Kelley, W. Lees, and S. Miller, 2020: Coastal heritage, global climate change, public engagement, and citizen science. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (15), 8280–8286. https://doi.org/10.1073/pnas.1912246117

53. Hambrecht, G. and M. Rockman, 2017: International approaches to climate change and cultural heritage. *American Antiquity*, **82** (4), 627–641. https://doi.org/10.1017/aaq.2017.30

54. AIA, 2022: Scalable Climate Action. American Institute of Architects, 28 pp. https://content.aia.org/sites/default/files/2022-03/21_10_EX_Scalable_Climate_Action_v03.pdf

55. ASLA, 2018: Smart Policies for a Changing Climate: The Report and Recommendations of the ASLA Blue Ribbon Panel on Climate Change and Resilience. American Society of Landscape Architects. https://www.asla.org/uploadedfiles/cms/about__us/climate_blue_ribbon/climate%20interactive3.pdf

56. IFMA, 2020: *Adapting to Climate Change for FM Professionals*. International Facility Management Association. https://knowledgelibrary.ifma.org/adapting-to-climate-change-for-fm-professionals/

57. International Code Council, 2021: 2021 International Building Code (IBC). International Code Council. https://codes.iccsafe.org/content/ibc2021p1

58. Rastogi, P., A. Laxo, L.D. Cecil, and D. Overbey, 2022: Projected climate data for building design: Barriers to use. *Buildings and Cities*, **3** (1), 111–117. https://doi.org/10.5334/bc.145

59. Ayyub, B.M., Ed. 2018: *Climate-Resilient Infrastructure: Adaptive Design and Risk Management*. American Society of Civil Engineers, Reston, VA. https://doi.org/10.1061/9780784415191

60. Chester, M.V., B.S. Underwood, and C. Samaras, 2020: Keeping infrastructure reliable under climate uncertainty. *Nature Climate Change*, **10** (6), 488–490. https://doi.org/10.1038/s41558-020-0741-0

61. Lopez-Cantu, T., A.F. Prein, and C. Samaras, 2020: Uncertainties in future U.S. extreme precipitation from downscaled climate projections. *Geophysical Research Letters*, **47** (9), e2019GL086797. https://doi.org/10.1029/2019gl086797

62. Patterson, M., 2022: Ch. 14. Resilience by design: Building facades for tomorrow. In: *Rethinking Building Skins*. Gasparri, E., A. Brambilla, G. Lobaccaro, F. Goia, A. Andaloro, and A. Sangiorgio, Eds. Woodhead Publishing, 359-375. https://doi.org/10.1016/b978-0-12-822477-9.00002-4

63. Underwood, B.S., G. Mascaro, M.V. Chester, A. Fraser, T. Lopez-Cantu, and C. Samaras, 2020: Past and present design practices and uncertainty in climate projections are challenges for designing infrastructure to future conditions. *Journal of Infrastructure Systems*, **26** (3), 04020026. https://doi.org/10.1061/(asce)is.1943-555x.0000567

64. Ray, P., N.B. Rajkovich, M.E. Tuzzo, M. Bohm, and B. Roberts, 2018: Regional Costs of Climate-Related Hazards for the New York State Building Sector. Report Number 18-11b. New York State Energy Research and Development Authority, Albany, NY. https://archplan.buffalo.edu/content/dam/ap/PDFs/NYSERDA/Regional-Costs-of-Climate-Related-Hazards.pdf

65. Maxim, A. and E. Grubert, 2021: Effects of climate migration on town-to-city transitions in the United States: Proactive investments in civil infrastructure for resilience and sustainability. *Environmental Research: Infrastructure and Sustainability*, **1** (3), 031001. https://doi.org/10.1088/2634-4505/ac33ef

66. Gomez, M., A. Mejia, B.L. Ruddell, and R.R. Rushforth, 2021: Supply chain diversity buffers cities against food shocks. *Nature*, **595** (7866), 250–254. https://doi.org/10.1038/s41586-021-03621-0

67. Sarkis, J., M.J. Cohen, P. Dewick, and P. Schröder, 2020: A brave new world: Lessons from the COVID-19 pandemic for transitioning to sustainable supply and production. *Resources, Conservation and Recycling*, **159**, 104894. https://doi.org/10.1016/j.resconrec.2020.104894

68. Simchi-Levi, D. and E. Simchi-Levi, 2020: We need a stress test for critical supply chains. *Harvard Business Review*. https://hbr.org/2020/04/we-need-a-stress-test-for-critical-supply-chains

69. Bezgrebelna, M., K. McKenzie, S. Wells, A. Ravindran, M. Kral, J. Christensen, V. Stergiopoulos, S. Gaetz, and S.A. Kidd, 2021: Climate change, weather, housing precarity, and homelessness: A systematic review of reviews. *International Journal of Environmental Research and Public Health*, **18** (11), 5812. https://doi.org/10.3390/ijerph18115812

70. Bixler, R.P., E. Yang, S.M. Richter, and M. Coudert, 2021: Boundary crossing for urban community resilience: A social vulnerability and multi-hazard approach in Austin, Texas, USA. *International Journal of Disaster Risk Reduction*, **66**, 102613. https://doi.org/10.1016/j.ijdrr.2021.102613

71. Hsu, A., G. Sheriff, T. Chakraborty, and D. Manya, 2021: Disproportionate exposure to urban heat island intensity across major US cities. *Nature Communications*, **12** (1), 2721. https://doi.org/10.1038/s41467-021-22799-5

72. Gabbe, C.J., G. Pierce, E. Petermann, and A. Marecek, 2021: Why and how do cities plan for extreme heat? *Journal of Planning Education and Research*, 0739456X211053654. https://doi.org/10.1177/0739456x211053654

73. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. https://doi.org/10.3390/cli8010012

74. Meerow, S. and L. Keith, 2022: Planning for extreme heat. *Journal of the American Planning Association*, **88** (3), 319–334. https://doi.org/10.1080/01944363.2021.1977682

75. Fragomeni, M.B.A., S. Bernardes, J.M. Shepherd, and R. Rivero, 2020: A collaborative approach to heat response planning: A case study to understand the integration of urban climatology and land-use planning. *Urban Climate*, **33**, 100653. https://doi.org/10.1016/j.uclim.2020.100653

76. Gronlund, C.J., K.P. Sullivan, Y. Kefelegn, L. Cameron, and M.S. O'Neill, 2018: Climate change and temperature extremes: A review of heat- and cold-related morbidity and mortality concerns of municipalities. *Maturitas*, **114**, 54–59. https://doi.org/10.1016/j.maturitas.2018.06.002

77. Lin, J. and R.D. Brown, 2021: Integrating microclimate into landscape architecture for outdoor thermal comfort: A systematic review. *Land*, **10** (2), 196. https://doi.org/10.3390/land10020196

78. Titus, J.G., 2023: Population in floodplains or close to sea level increased in US but declined in some counties—Especially among black residents. *Environmental Research Letters*, **18** (3), 034001. https://doi.org/10.1088/1748-9326/acadf5

79. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

80. Harlan, S.L., P. Chakalian, J. Declet-Barreto, D.M. Hondula, and G.D. Jenerette, 2019: Ch. 2. Pathways to climate justice in a desert metropolis. In: *People and Climate Change: Vulnerability, Adaptation, and Social Justice*. Reyes Mason, L. and J. Rigg, Eds. Oxford University Press, 23–50. https://doi.org/10.1093/oso/9780190886455.003.0002

81. Eguiluz-Gracia, I., A.G. Mathioudakis, S. Bartel, S.J.H. Vijverberg, E. Fuertes, P. Comberiati, Y.S. Cai, P.V. Tomazic, Z. Diamant, J. Vestbo, C. Galan, and B. Hoffmann, 2020: The need for clean air: The way air pollution and climate change affect allergic rhinitis and asthma. *Allergy*, **75** (9), 2170–2184. https://doi.org/10.1111/all.14177

82. Karnauskas, K.B., S.L. Miller, and A.C. Schapiro, 2020: Fossil fuel combustion is driving indoor $CO_2$ toward levels harmful to human cognition. *GeoHealth*, **4** (5), e2019GH000237. https://doi.org/10.1029/2019gh000237

83. Lebel, E.D., C.J. Finnegan, Z. Ouyang, and R.B. Jackson, 2022: Methane and NOx emissions from natural gas stoves, cooktops, and ovens in residential homes. *Environmental Science & Technology*, **56** (4), 2529–2539. https://doi.org/10.1021/acs.est.1c04707

84. Evans, G.W., 2019: Projected behavioral impacts of global climate change. *Annual Review of Psychology*, **70** (1), 449–474. https://doi.org/10.1146/annurev-psych-010418-103023

85. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

86. Martinich, J. and A. Crimmins, 2019: Climate damages and adaptation potential across diverse sectors of the United States. *Nature Climate Change*, **9** (5), 397–404. https://doi.org/10.1038/s41558-019-0444-6

87. Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372** (6549), 8054. https://doi.org/10.1126/science.abc8054

88. Hausfather, Z. and G.P. Peters, 2020: Emissions—The 'business as usual' story is misleading. *Nature*, **577** (7792), 618–620. https://doi.org/10.1038/d41586-020-00177-3

89. OSTP, 2023: Selecting Climate Information to Use in Climate Risk and Impact Assessments: Guide for Federal Agency Climate Adaptation Planners. White House Office of Science and Technology Policy, Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2023/03/guide-on-selecting-climate-information-to-use-in-climate-risk-and-impact-assessments.pdf

90. Schwalm, C.R., S. Glendon, and P.B. Duffy, 2020: RCP8.5 tracks cumulative $CO_2$ emissions. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (33), 19656–19657. https://doi.org/10.1073/pnas.2007117117

91. Neumann, J.E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich, 2021: Climate effects on US infrastructure: The economics of adaptation for rail, roads, and coastal development. *Climatic Change*, **167** (3), 44. https://doi.org/10.1007/s10584-021-03179-w

92. Hauer, M.E., E. Fussell, V. Mueller, M. Burkett, M. Call, K. Abel, R. McLeman, and D. Wrathall, 2020: Sea-level rise and human migration. *Nature Reviews Earth & Environment*, **1** (1), 28–39. https://doi.org/10.1038/s43017-019-0002-9

93. Goldstein, A., W.R. Turner, J. Gladstone, and D.G. Hole, 2019: The private sector's climate change risk and adaptation blind spots. *Nature Climate Change*, **9** (1), 18–25. https://doi.org/10.1038/s41558-018-0340-5

94. Keenan, J.M. and J.T. Bradt, 2020: Underwaterwriting: From theory to empiricism in regional mortgage markets in the U.S. *Climatic Change*, **162** (4), 2043–2067. https://doi.org/10.1007/s10584-020-02734-1

95. Owen, R., 2019: Actuaries are paying attention to climate data. *Bulletin of the American Meteorological Society*, **100** (1), S5–S8. https://doi.org/10.1175/bams-d-18-0293.1

96. Bakkensen, L.A. and L. Barrage, 2022: Going underwater? Flood risk belief heterogeneity and coastal home price dynamics. *The Review of Financial Studies*, **35** (8), 3666–3709. https://doi.org/10.1093/rfs/hhab122

97. Beck, J. and M. Lin, 2020: The impact of sea level rise on real estate prices in coastal Georgia. *Review of Regional Studies*, **50** (1), 43–52. https://doi.org/10.52324/001c.11643

98. Bernstein, A., M.T. Gustafson, and R. Lewis, 2019: Disaster on the horizon: The price effect of sea level rise. *Journal of Financial Economics*, **134** (2), 253–272. https://doi.org/10.1016/j.jfineco.2019.03.013

99. Hino, M. and M. Burke, 2021: The effect of information about climate risk on property values. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (17), e2003374118. https://doi.org/10.1073/pnas.2003374118

100. Kim, S.K. and R.B. Peiser, 2020: The implication of the increase in storm frequency and intensity to coastal housing markets. *Journal of Flood Risk Management*, **13** (3), e12626. https://doi.org/10.1111/jfr3.12626

101. Duanmu, J., Y. Li, M. Lin, and S. Tahsin, 2022: Natural disaster risk and residential mortgage lending standards. *Journal of Real Estate Research*, **44** (1), 106–130. https://doi.org/10.1080/08965803.2021.2013613

102. Baldauf, M., L. Garlappi, and C. Yannelis, 2020: Does climate change affect real estate prices? Only if you believe in it. *The Review of Financial Studies*, **33** (3), 1256–1295. https://doi.org/10.1093/rfs/hhz073

103. Barrage, L. and J. Furst, 2019: Housing investment, sea level rise, and climate change beliefs. *Economics Letters*, **177**, 105–108. https://doi.org/10.1016/j.econlet.2019.01.023

104. Markolf, S.A., I.M. Azevedo, M. Muro, and D.G. Victor, 2020: Pledges and Progress: Steps Toward Greenhouse Gas Emissions Reductions in the 100 Largest Cities Across the United States. The Brookings Institution. https://www.brookings.edu/wp-content/uploads/2020/10/fp_20201022_ghg_pledges_v4.pdf

105. Woodruff, S.C., 2022: Coordinating plans for climate adaptation. *Journal of Planning Education and Research*, **42** (2), 218–230. https://doi.org/10.1177/0739456x18810131

106. Kalesnikaite, V., 2019: Keeping cities afloat: Climate change adaptation and collaborative governance at the local level. *Public Performance & Management Review*, **42** (4), 864–888. https://doi.org/10.1080/15309576.2018.1526091

107. Rai, S., 2020: Policy adoption and policy intensity: Emergence of climate adaptation planning in U.S. states. *Review of Policy Research*, **37** (4), 444–463. https://doi.org/10.1111/ropr.12383

108. Siders, A.R. and J.M. Keenan, 2020: Variables shaping coastal adaptation decisions to armor, nourish, and retreat in North Carolina. *Ocean & Coastal Management*, **183**, 105023. https://doi.org/10.1016/j.ocecoaman.2019.105023

109. U.S. Federal Government, 2014: U.S. Climate Resilience Toolkit [Website]. http://toolkit.climate.gov

110. NIHHIS, 2022: National Integrated Heat Health Information System [Website]. https://www.heat.gov

111. FEMA, 2023: Hazard Mitigation Plan Status. U.S. Department of Homeland Security, Federal Emergency Management Agency, accessed July 6, 2023. https://www.fema.gov/emergency-managers/risk-management/hazard-mitigation-planning/status

112. Stults, M. and L. Larsen, 2020: Tackling uncertainty in US local climate adaptation planning. *Journal of Planning Education and Research*, **40** (4), 416–431. https://doi.org/10.1177/0739456x18769134

113. Phius, 2022: Phius Standards [Website]. https://www.phius.org/standards

114. NGBS, 2022: The NGBS Green Promise. National Green Building Standard. https://www.ngbs.com/the-ngbs-green-promise

115. Gong, F.-Y., Z.-C. Zeng, F. Zhang, X. Li, E. Ng, and L.K. Norford, 2018: Mapping sky, tree, and building view factors of street canyons in a high-density urban environment. *Building and Environment*, **134**, 155–167. https://doi.org/10.1016/j.buildenv.2018.02.042

116. González, J.E., P. Ramamurthy, R.D. Bornstein, F. Chen, E.R. Bou-Zeid, M. Ghandehari, J. Luvall, C. Mitra, and D. Niyogi, 2021: Urban climate and resiliency: A synthesis report of state of the art and future research directions. *Urban Climate*, **38**, 100858. https://doi.org/10.1016/j.uclim.2021.100858

117. Grêt-Regamey, A., M. Switalski, N. Fagerholm, S. Korpilo, S. Juhola, M. Kyttä, N. Käyhkö, T. McPhearson, M. Nollert, T. Rinne, N. Soininen, T. Toivonen, A. Räsänen, E. Willberg, and C.M. Raymond, 2021: Harnessing sensing systems towards urban sustainability transformation. *npj Urban Sustainability*, **1** (1), 40. https://doi.org/10.1038/s42949-021-00042-w

118. Liang, J., J. Gong, J. Sun, J. Zhou, W. Li, Y. Li, J. Liu, and S. Shen, 2017: Automatic sky view factor estimation from Street View photographs—A big data approach. *Remote Sensing*, **9** (5), 411. https://doi.org/10.3390/rs9050411

119. Masson, V., W. Heldens, E. Bocher, M. Bonhomme, B. Bucher, C. Burmeister, C. de Munck, T. Esch, J. Hidalgo, F. Kanani-Sühring, Y.-T. Kwok, A. Lemonsu, J.-P. Lévy, B. Maronga, D. Pavlik, G. Petit, L. See, R. Schoetter, N. Tornay, A. Votsis, and J. Zeidler, 2020: City-descriptive input data for urban climate models: Model requirements, data sources and challenges. *Urban Climate*, **31**, 100536. https://doi.org/10.1016/j.uclim.2019.100536

120. Middel, A., J. Lukasczyk, R. Maciejewski, M. Demuzere, and M. Roth, 2018: Sky view factor footprints for urban climate modeling. *Urban Climate*, **25**, 120–134. https://doi.org/10.1016/j.uclim.2018.05.004

121. Middel, A., J. Lukasczyk, S. Zakrzewski, M. Arnold, and R. Maciejewski, 2019: Urban form and composition of street canyons: A human-centric big data and deep learning approach. *Landscape and Urban Planning*, **183**, 122–132. https://doi.org/10.1016/j.landurbplan.2018.12.001

122. Carmin, J., K. Tierney, E. Chu, L.M. Hunter, J.T. Roberts, and L. Shi, 2015: Ch. 6. Adaptation to climate change. In: *Climate Change and Society: Sociological Perspectives*. Dunlap, R.E. and R.J. Brulle, Eds. Oxford University Press, 164–198. https://doi.org/10.1093/acprof:oso/9780199356102.003.0006

123. Dodman, D., B. Hayward, M. Pelling, V. Castan Broto, W. Chow, E. Chu, R. Dawson, L. Khirfan, T. McPhearson, A. Prakash, Y. Zheng, and G. Ziervogel, 2022: Ch. 6. Cities, settlements and key infrastructure. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 907–1040. https://doi.org/10.1017/9781009325844.008

124. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–33. https://doi.org/10.1017/9781009325844.001

125. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.001

126. Zhang, Y. and M. Ayyub Bilal, 2020: Electricity system assessment and adaptation to rising temperatures in a changing climate using Washington metro area as a case study. *Journal of Infrastructure Systems*, **26** (2), 04020017. https://doi.org/10.1061/(asce)is.1943-555x.0000550

127. Hsu, D., T. Meng, A. Han, and D. Suh, 2019: Further opportunities to reduce the energy use and greenhouse gas emissions of buildings. *Journal of Planning Education and Research*, **39** (3), 315–331. https://doi.org/10.1177/0739456x17739674

128. Zhang, Y. and B.M. Ayyub, 2020: Projecting heat waves temporally and spatially for local adaptations in a changing climate: Washington D.C. as a case study. *Natural Hazards*, **103** (1), 731–750. https://doi.org/10.1007/s11069-020-04008-6

129. Smalls-Mantey, L. and F. Montalto, 2021: The seasonal microclimate trends of a large scale extensive green roof. *Building and Environment*, **197**, 107792. https://doi.org/10.1016/j.buildenv.2021.107792

130. Kumar, N., M. Barbato, and R. Holton, 2018: Feasibility study of affordable earth masonry housing in the U.S. Gulf Coast Region. *Journal of Architectural Engineering*, **24** (2), 04018009. https://doi.org/10.1061/(asce)ae.1943-5568.0000311

131. Reda Taha, M., M. Ayyub Bilal, K. Soga, S. Daghash, D. Heras Murcia, F. Moreu, and E. Soliman, 2021: Emerging technologies for resilient infrastructure: Conspectus and roadmap. ASCE-ASME *Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, **7** (2), 03121002. https://doi.org/10.1061/ajrua6.0001134

132. Skillington, K., R.H. Crawford, G. Warren-Myers, and K. Davidson, 2022: A review of existing policy for reducing embodied energy and greenhouse gas emissions of buildings. *Energy Policy*, **168**, 112920. https://doi.org/10.1016/j.enpol.2022.112920

133. Hurlimann, A., S. Moosavi, and G.R. Browne, 2021: Urban planning policy must do more to integrate climate change adaptation and mitigation actions. *Land Use Policy*, **101**, 105188. https://doi.org/10.1016/j.landusepol.2020.105188

134. Zhang, H., J. Peng, R. Wang, J. Zhang, and D. Yu, 2021: Spatial planning factors that influence $CO_2$ emissions: A systematic literature review. *Urban Climate*, **36**, 100809. https://doi.org/10.1016/j.uclim.2021.100809

135. Slowik, P. and N. Lutsey, 2018: The Continued Transition to Electric Vehicles in U.S. Cities. International Council on Clean Transportation, Washington, DC. https://theicct.org/publication/the-continued-transition-to-electric-vehicles-in-u-s-cities/

136. Jenn, A., J.H. Lee, S. Hardman, and G. Tal, 2020: An in-depth examination of electric vehicle incentives: Consumer heterogeneity and changing response over time. *Transportation Research Part A: Policy and Practice*, **132**, 97–109. https://doi.org/10.1016/j.tra.2019.11.004

137. Jenn, A., K. Springel, and A.R. Gopal, 2018: Effectiveness of electric vehicle incentives in the United States. *Energy Policy*, **119**, 349–356. https://doi.org/10.1016/j.enpol.2018.04.065

138. Wee, S., M. Coffman, and S. La Croix, 2018: Do electric vehicle incentives matter? Evidence from the 50 U.S. states. *Research Policy*, **47** (9), 1601–1610. https://doi.org/10.1016/j.respol.2018.05.003

139. Fung, J.F., J.F. Helgeson, D.H. Webb, C.M. O'Fallon, and H. Cutler, 2021: Does resilience yield dividends? Co-benefits of investing in increased resilience in Cedar Rapids. *Economic Systems Research*, **33** (3), 336–362. https://doi.org/10.1080/09535314.2020.1798359

140. Kondo, K., L. Mabon, Y. Bi, Y. Chen, and Y. Hayabuchi, 2021: Balancing conflicting mitigation and adaptation behaviours of urban residents under climate change and the urban heat island effect. *Sustainable Cities and Society*, **65**, 102585. https://doi.org/10.1016/j.scs.2020.102585

141. Negev, M., L. Zea-Reyes, L. Caputo, G. Weinmayr, C. Potter, and A. de Nazelle, 2022: Barriers and enablers for integrating public health cobenefits in urban climate policy. *Annual Review of Public Health*, **43** (1), 255–270. https://doi.org/10.1146/annurev-publhealth-052020-010820

142. Sethi, M., 2020: Ch. 17. Climate co-benefits in rapidly urbanizing emerging economies: Scientific and policy imperatives. In: *Ancillary Benefits of Climate Policy: New Theoretical Developments and Empirical Findings*. Buchholz, W., A. Markandya, D. Rübbelke, and S. Vögele, Eds. Springer, Cham, Switzerland, 301–324. https://doi.org/10.1007/978-3-030-30978-7_17

143. Sharifi, A., 2021: Co-benefits and synergies between urban climate change mitigation and adaptation measures: A literature review. *Science of The Total Environment*, **750**, 141642. https://doi.org/10.1016/j.scitotenv.2020.141642

144. Lwasa, S., K.C. Seto, X. Bai, H. Blanco, K.R. Gurney, S. Kilkiş, O. Lucon, J. Murakami, J. Pan, A. Sharifi, and Y. Yamagata, 2022: Ch. 8. Urban systems and other settlements. In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 861–952. https://doi.org/10.1017/9781009157926.010

145. Ward, S., C. Staddon, L. De Vito, A. Zuniga-Teran, A.K. Gerlak, Y. Schoeman, A. Hart, and G. Booth, 2019: Embedding social inclusiveness and appropriateness in engineering assessment of green infrastructure to enhance urban resilience. *Urban Water Journal*, **16** (1), 56–67. https://doi.org/10.1080/1573062x.2019.1633674

146. Webb, B., B. Dix, S. Douglass, S. Asam, C. Cherry, and B. Buhring, 2019: Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide. FHWA-HEP-19-042. U.S. Department of Transportation, Federal Highway Administration, Washington DC. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/implementation_guide/

147. Keith, L. and S. Meerow, 2022: Planning for Urban Heat Resilience. PAS Report 600. American Planning Association, 99 pp. https://www.planning.org/publications/report/9245695/

148. Zheng, X., Y. Zou, A.W. Lounsbury, C. Wang, and R. Wang, 2021: Green roofs for stormwater runoff retention: A global quantitative synthesis of the performance. *Resources, Conservation and Recycling*, **170**, 105577. https://doi.org/10.1016/j.resconrec.2021.105577

149. Besir, A.B. and E. Cuce, 2018: Green roofs and facades: A comprehensive review. *Renewable and Sustainable Energy Reviews*, **82**, 915–939. https://doi.org/10.1016/j.rser.2017.09.106

150. Jamei, E., H.W. Chau, M. Seyedmahmoudian, and A. Stojcevski, 2021: Review on the cooling potential of green roofs in different climates. *Science of The Total Environment*, **791**, 148407. https://doi.org/10.1016/j.scitotenv.2021.148407

151. Susca, T., 2019: Green roofs to reduce building energy use? A review on key structural factors of green roofs and their effects on urban climate. *Building and Environment*, **162**, 106273. https://doi.org/10.1016/j.buildenv.2019.106273

152. Wong, N.H., C.L. Tan, D.D. Kolokotsa, and H. Takebayashi, 2021: Greenery as a mitigation and adaptation strategy to urban heat. *Nature Reviews Earth & Environment*, **2** (3), 166–181. https://doi.org/10.1038/s43017-020-00129-5

153. Matsler, A.M., 2019: Making 'green' fit in a 'grey' accounting system: The institutional knowledge system challenges of valuing urban nature as infrastructural assets. *Environmental Science & Policy*, **99**, 160–168. https://doi.org/10.1016/j.envsci.2019.05.023

154. Chester, M., B.S. Underwood, B. Allenby, M. Garcia, C. Samaras, S. Markolf, K. Sanders, B. Preston, and T.R. Miller, 2021: Infrastructure resilience to navigate increasingly uncertain and complex conditions in the Anthropocene. *npj Urban Sustainability*, **1** (1), 4. https://doi.org/10.1038/s42949-021-00016-y

155. Mahmoud, H., 2020: Barriers to gauging built environment climate vulnerability. *Nature Climate Change*, **10** (6), 482–485. https://doi.org/10.1038/s41558-020-0742-z

156. Markolf, S.A., M.V. Chester, D.A. Eisenberg, D.M. Iwaniec, C.I. Davidson, R. Zimmerman, T.R. Miller, B.L. Ruddell, and H. Chang, 2018: Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience. *Earth's Future*, **6** (12), 1638–1659. https://doi.org/10.1029/2018ef000926

157. Mehvar, S., K. Wijnberg, B. Borsje, N. Kerle, J.M. Schraagen, J. Vinke-de Kruijf, K. Geurs, A. Hartmann, R. Hogeboom, and S. Hulscher, 2021: Review article: Towards resilient vital infrastructure systems—Challenges, opportunities, and future research agenda. *Natural Hazards and Earth System Sciences*, **21** (5), 1383–1407. https://doi.org/10.5194/nhess-21-1383-2021

158. WUCA, 2021: Leading Practices in Climate Adaptation. Water Utility Climate Alliance. https://www.wucaonline.org/adaptation-in-practice/leading-practices

159. Lopez-Cantu, T., M.K. Webber, and C. Samaras, 2022: Incorporating uncertainty from downscaled rainfall projections into climate resilience planning in U.S. cities. *Environmental Research: Infrastructure and Sustainability*, **2** (4), 045006. https://doi.org/10.1088/2634-4505/ac8a6c

160. OWP, 2022: Analysis of Impact of Nonstationary Climate on NOAA Atlas 14 Estimates: Assessment Report. National Oceanic and Atmospheric Administration, National Weather Service, Office of Water Prediction. https://hdsc.nws.noaa.gov/pfds/files25/NA14_Assessment_report_202201v1.pdf

161. Chang, H., A. Pallathadka, J. Sauer, N.B. Grimm, R. Zimmerman, C. Cheng, D.M. Iwaniec, Y. Kim, R. Lloyd, T. McPhearson, B. Rosenzweig, T. Troxler, C. Welty, R. Brenner, and P. Herreros-Cantis, 2021: Assessment of urban flood vulnerability using the social-ecological-technological systems framework in six US cities. *Sustainable Cities and Society*, **68**, 102786. https://doi.org/10.1016/j.scs.2021.102786

162. Deetjen, T.A., J.P. Conger, B.D. Leibowicz, and M.E. Webber, 2018: Review of climate action plans in 29 major U.S. cities: Comparing current policies to research recommendations. *Sustainable Cities and Society*, **41**, 711–727. https://doi.org/10.1016/j.scs.2018.06.023

163. Fastiggi, M., S. Meerow, and T.R. Miller, 2021: Governing urban resilience: Organisational structures and coordination strategies in 20 North American city governments. *Urban Studies*, **58** (6), 1262–1285. https://doi.org/10.1177/0042098020907277

164. Hsu, A. and R. Rauber, 2021: Diverse climate actors show limited coordination in a large-scale text analysis of strategy documents. *Communications Earth & Environment*, **2** (1), 30. https://doi.org/10.1038/s43247-021-00098-7

165. Koutra, S., M. Balsells Mondejar, and V. Becue, 2022: The nexus of 'urban resilience' and 'energy efficiency' in cities. *Current Research in Environmental Sustainability*, **4**, 100118. https://doi.org/10.1016/j.crsust.2021.100118

166. Woodruff, S., A.O. Bowman, B. Hannibal, G. Sansom, and K. Portney, 2021: Urban resilience: Analyzing the policies of U.S. cities. *Cities*, **115**, 103239. https://doi.org/10.1016/j.cities.2021.103239

167. Boswell, M.R., A.I. Greve, and T.L. Seale, 2019: *Climate Action Planning: A Guide to Creating Low-Carbon, Resilient Communities*. Island Press, Washington, DC, 365 pp. https://doi.org/10.5822/978-1-61091-964-7

168. Landis, J.D., D. Hsu, and E. Guerra, 2019: Intersecting residential and transportation $CO_2$ emissions: Metropolitan climate change programs in the age of Trump. *Journal of Planning Education and Research*, **39** (2), 206–226. https://doi.org/10.1177/0739456x17729438

169. Chu, E.K. and C.E.B. Cannon, 2021: Equity, inclusion, and justice as criteria for decision-making on climate adaptation in cities. *Current Opinion in Environmental Sustainability*, **51**, 85–94. https://doi.org/10.1016/j.cosust.2021.02.009

170. Patterson, J.J., 2021: More than planning: Diversity and drivers of institutional adaptation under climate change in 96 major cities. *Global Environmental Change*, **68**, 102279. https://doi.org/10.1016/j.gloenvcha.2021.102279

171. Keith, L., S. Meerow, D.M. Hondula, V.K. Turner, and J.C. Arnott, 2021: Deploy heat officers, policies and metrics. *Nature*, **598** (7879), 29–31. https://doi.org/10.1038/d41586-021-02677-2

172. Hughes, S., E.K. Chu, and S.G. Mason, Eds., 2018: *Climate Change in Cities: Innovations in Multi-Level Governance*. 1st ed. The Urban Book Series. Springer, Cham, Switzerland, 378 pp. https://doi.org/10.1007/978-3-319-65003-6

173. National BPS Coalition, 2021: The National Building Performance Standards Coalition. Institute for Market Transformation. https://nationalbpscoalition.org

174. Bellinson, R. and E. Chu, 2019: Learning pathways and the governance of innovations in urban climate change resilience and adaptation. *Journal of Environmental Policy & Planning*, **21** (1), 76–89. https://doi.org/10.1080/1523908x.2018.1493916

175. Keeler, A.G., D.E. McNamara, and J.L. Irish, 2018: Responding to sea level rise: Does short-term risk reduction inhibit successful long-term adaptation? *Earth's Future*, **6** (4), 618–621. https://doi.org/10.1002/2018ef000828

176. Solecki, W., G.C. Delgado Ramos, D. Roberts, C. Rosenzweig, and B. Walsh, 2021: Accelerating climate research and action in cities through advanced science-policy-practice partnerships. *Npj Urban Sustainability*, **1** (1), 3. https://doi.org/10.1038/s42949-021-00015-z

177. Woodruff, S.C., 2018: City membership in climate change adaptation networks. *Environmental Science & Policy*, **84**, 60–68. https://doi.org/10.1016/j.envsci.2018.03.002

178. Cannon, C., E. Chu, A. Natekal, and G. Waaland, 2023: Translating and embedding equity-thinking into climate adaptation: An analysis of US cities. *Regional Environmental Change*, **23** (1), 30. https://doi.org/10.1007/s10113-023-02025-2

179. Fink, J.H., 2019: Contrasting governance learning processes of climate-leading and -lagging cities: Portland, Oregon, and Phoenix, Arizona, USA. *Journal of Environmental Policy and Planning*, **21** (1), 16–29. https://doi.org/10.1080/1523908x.2018.1487280.

180. Hsu, D., 2022: Straight out of Cape Cod: The origin of community choice aggregation and its spread to other states. *Energy Research & Social Science*, **86**, 102393. https://doi.org/10.1016/j.erss.2021.102393

181. Hui, I., G. Smith, and C. Kimmel, 2019: Think globally, act locally: Adoption of climate action plans in California. *Climatic Change*, **155** (4), 489–509. https://doi.org/10.1007/s10584-019-02505-7

182. Leffel, B., 2022: Toward global urban climate mitigation: Linking national and polycentric systems of environmental change. *Sociology of Development*, **8** (1), 111–137. https://doi.org/10.1525/sod.2021.0018

183. Miao, Q., 2019: What affects government planning for climate change adaptation: Evidence from the U.S. states. *Environmental Policy and Governance*, **29** (5), 376–394. https://doi.org/10.1002/eet.1866

184. Moser, S.C., J.A. Ekstrom, J. Kim, and S. Heitsch, 2019: Adaptation finance archetypes: Local governments' persistent challenges of funding adaptation to climate change and ways to overcome them. *Ecology and Society*, **24** (2), 28. https://doi.org/10.5751/es-10980-240228

185. Gilmore, E.A. and T. St.Clair, 2018: Budgeting for climate change: Obstacles and opportunities at the US state level. *Climate Policy*, **18** (6), 729–741. https://doi.org/10.1080/14693062.2017.1366891

186. Javadi, S. and A.-A. Masum, 2021: The impact of climate change on the cost of bank loans. *Journal of Corporate Finance*, **69**, 102019. https://doi.org/10.1016/j.jcorpfin.2021.102019

187. Shi, L. and A.M. Varuzzo, 2020: Surging seas, rising fiscal stress: Exploring municipal fiscal vulnerability to climate change. *Cities*, **100**, 102658. https://doi.org/10.1016/j.cities.2020.102658

188. Young, S.A., K.C. Lindeman, and S.R. Fowler, 2022: Climate adaptation and risk preparedness in Florida's East Coast cities: Views of municipal leaders. *Journal of Environmental Planning and Management*, 1–15. https://doi.org/10.1080/09640568.2022.2125369

189. Cousins, J.J. and D.T. Hill, 2021: Green infrastructure, stormwater, and the financialization of municipal environmental governance. *Journal of Environmental Policy & Planning*, **23** (5), 581–598. https://doi.org/10.1080/1523908x.2021.1893164

190. Klein, J., M. Araos, A. Karimo, M. Heikkinen, T. Ylä-Anttila, and S. Juhola, 2018: The role of the private sector and citizens in urban climate change adaptation: Evidence from a global assessment of large cities. *Global Environmental Change*, **53**, 127–136. https://doi.org/10.1016/j.gloenvcha.2018.09.012

191. Painter, M., 2020: An inconvenient cost: The effects of climate change on municipal bonds. *Journal of Financial Economics*, **135** (2), 468–482. https://doi.org/10.1016/j.jfineco.2019.06.006

192. Rashidi, K., M. Stadelmann, and A. Patt, 2019: Creditworthiness and climate: Identifying a hidden financial co-benefit of municipal climate adaptation and mitigation policies. *Energy Research & Social Science*, **48**, 131–138. https://doi.org/10.1016/j.erss.2018.09.021

193. Chung, C.S., 2020: Rising tides and rearranging deckchairs: How climate change is reshaping infrastructure finance and threatening to sink municipal budgets. *Georgetown Enviornmental Law Review*, **32** (2), 165–226. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3452590

194. Bigger, P. and N. Millington, 2020: Getting soaked? Climate crisis, adaptation finance, and racialized austerity. *Environment and Planning E: Nature and Space*, **3** (3), 601–623. https://doi.org/10.1177/2514848619876539

195. Giglio, S., B. Kelly, and J. Stroebel, 2021: Climate finance. *Annual Review of Financial Economics*, **13** (1), 15–36. https://doi.org/10.1146/annurev-financial-102620-103311

196. Jinga, P., 2021: Ch. 16. The increasing importance of environmental, social and governance (ESG) investing in combating climate change. In: *Environmental Management*. Tiefenbacher, J.P., Ed. IntechOpen. https://doi.org/10.5772/intechopen.98345

197. Partridge, C. and F.R. Medda, 2020: The evolution of pricing performance of green municipal bonds. *Journal of Sustainable Finance & Investment*, **10** (1), 44–64. https://doi.org/10.1080/20430795.2019.1661187

198. Angelo, H., K. MacFarlane, J. Sirigotis, and A. Millard-Ball, 2022: Missing the housing for the trees: Equity in urban climate planning. *Journal of Planning Education and Research*, 0739456X211072527. https://doi.org/10.1177/0739456x211072527

199. Meerow, S., P. Pajouhesh, and T.R. Miller, 2019: Social equity in urban resilience planning. *Local Environment*, **24** (9), 793–808. https://doi.org/10.1080/13549839.2019.1645103

200. Shi, L., 2021: From progressive cities to resilient cities: Lessons from history for new debates in equitable adaptation to climate change. *Urban Affairs Review*, **57** (5), 1442–1479. https://doi.org/10.1177/1078087419910827

201. Berrang-Ford, L., A.R. Siders, A. Lesnikowski, A.P. Fischer, M.W. Callaghan, et al., 2021: A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, **11** (11), 989–1000. https://doi.org/10.1038/s41558-021-01170-y

202. Olazabal, M., M. Ruiz de Gopegui, E.L. Tompkins, K. Venner, and R. Smith, 2019: A cross-scale worldwide analysis of coastal adaptation planning. *Environmental Research Letters*, **14** (12), 124056. https://doi.org/10.1088/1748-9326/ab5532

203. Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, **62**, 102071. https://doi.org/10.1016/j.gloenvcha.2020.102071

204. Fiack, D., J. Cumberbatch, M. Sutherland, and N. Zerphey, 2021: Sustainable adaptation: Social equity and local climate adaptation planning in U.S. cities. *Cities*, **115**, 103235. https://doi.org/10.1016/j.cities.2021.103235

205. Johnson, K.A., O.E.J. Wing, P.D. Bates, J. Fargione, T. Kroeger, W.D. Larson, C.C. Sampson, and A.M. Smith, 2020: A benefit–cost analysis of floodplain land acquisition for US flood damage reduction. *Nature Sustainability*, **3** (1), 56–62. https://doi.org/10.1038/s41893-019-0437-5

206. Gourevitch, J.D., R.M. Diehl, B.C. Wemple, and T.H. Ricketts, 2022: Inequities in the distribution of flood risk under floodplain restoration and climate change scenarios. *People and Nature*, **4** (2), 415–427. https://doi.org/10.1002/pan3.10290

207. Parton, L.C. and S.J. Dundas, 2020: Fall in the sea, eventually? A green paradox in climate adaptation for coastal housing markets. *Journal of Environmental Economics and Management*, **104**, 102381. https://doi.org/10.1016/j.jeem.2020.102381

208. Dundon, L.A. and M. Abkowitz, 2021: Climate-induced managed retreat in the U.S.: A review of current research. *Climate Risk Management*, **33**, 100337. https://doi.org/10.1016/j.crm.2021.100337

209. Katavoutas, G., H.A. Flocas, and A. Matzarakis, 2015: Dynamic modeling of human thermal comfort after the transition from an indoor to an outdoor hot environment. *International Journal of Biometeorology*, **59** (2), 205–216. https://doi.org/10.1007/s00484-014-0836-2

210. Stone Jr., B., K. Lanza, E. Mallen, J. Vargo, and A. Russell, 2023: Urban heat management in Louisville, Kentucky: A framework for climate adaptation planning. *Journal of Planning Education and Research*, **43** (2), 346–358. https://doi.org/10.1177/0739456x19879214

211. Sun, K., M. Specian, and T. Hong, 2020: Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home. *Building and Environment*, **177**, 106842. https://doi.org/10.1016/j.buildenv.2020.106842

212. Zhao, Q., C. Dickson, J. Thornton, P. Solís, and E.A. Wentz, 2020: Articulating strategies to address heat resilience using spatial optimization and temporal analysis of utility assistance data of the Salvation Army Metro Phoenix. *Applied Geography*, **122**, 102241. https://doi.org/10.1016/j.apgeog.2020.102241

213. Ortiz, M., L. Itard, and P.M. Bluyssen, 2020: Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review. *Energy and Buildings*, **221**, 110102. https://doi.org/10.1016/j.enbuild.2020.110102

214. Jessel, S., S. Sawyer, and D. Hernández, 2019: Energy, poverty, and health in climate change: A comprehensive review of an emerging literature. *Frontiers in Public Health*, **7**, 357. https://doi.org/10.3389/fpubh.2019.00357

215. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

216. Tedesco, M., J.M. Keenan, and C. Hultquist, 2022: Measuring, mapping, and anticipating climate gentrification in Florida: Miami and Tampa case studies. *Cities*, **131**, 103991. https://doi.org/10.1016/j.cities.2022.103991

217. Aune, K.T., D. Gesch, and G.S. Smith, 2020: A spatial analysis of climate gentrification in Orleans Parish, Louisiana post-Hurricane Katrina. *Environmental Research*, **185**, 109384. https://doi.org/10.1016/j.envres.2020.109384

218. Sarzynski, A., 2018: Ch. 6. Multi-level governance, civic capacity, and overcoming the climate change "adaptation deficit" in Baltimore, Maryland. In: *Climate Change in Cities: Innovations in Multi-Level Governance*. Hughes, S., E.K. Chu, and S.G. Mason, Eds. Springer, Cham, Switzerland, 97-120. https://doi.org/10.1007/978-3-319-65003-6_6

219. van den Berg, H.J. and J.M. Keenan, 2019: Dynamic vulnerability in the pursuit of just adaptation processes: A Boston case study. *Environmental Science & Policy*, **94**, 90–100. https://doi.org/10.1016/j.envsci.2018.12.015

220. Guardaro, M., M. Messerschmidt, D.M. Hondula, N.B. Grimm, and C.L. Redman, 2020: Building community heat action plans story by story: A three neighborhood case study. *Cities*, **107**, 102886. https://doi.org/10.1016/j.cities.2020.102886

221. Baja, K., 2021: Ch. 6. Resilience hubs: Shifting power to communities through action. In: *Climate Adaptation and Resilience Across Scales: From Buildings to Cities*. Rajkovich, N.B. and S.H. Holmes, Eds. Routledge, New York, 21. https://doi.org/10.4324/9781003030720

222. HUD, 2023: Citizen Participation & Equitable Engagement (CPEE) Toolkit. U.S. Department of Housing and Urban Development, accessed August 3, 2023. https://www.hudexchange.info/programs/cdbg-dr/cpee-toolkit/introduction/

223. Woodruff, S.C., S. Meerow, M. Stults, and C. Wilkins, 2022: Adaptation to resilience planning: Alternative pathways to prepare for climate change. *Journal of Planning Education and Research*, **42** (1), 64–75. https://doi.org/10.1177/0739456x18801057

224. Chu, E., T. Schenk, and J. Patterson, 2018: The dilemmas of citizen inclusion in urban planning and governance to enable a 1.5°C climate change scenario. *Urban Planning*, **3** (2), 128–40. https://doi.org/10.17645/up.v3i2.1292.

225. Iwaniec, D.M., N.B. Grimm, T. McPhearson, M. Berbés-Blázquez, E.M. Cook, and T.A. Muñoz-Erickson, 2021: Ch. 1. A framework for resilient urban futures. In: *Resilient Urban Futures*. Hamstead, Z.A., D.M. Iwaniec, T. McPhearson, M. Berbés-Blázquez, E.M. Cook, and T.A. Muñoz-Erickson, Eds. Springer, Cham, Switzerland, 1–9. https://doi.org/10.1007/978-3-030-63131-4_1

226. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

227. Rudge, K., 2021: Participatory climate adaptation planning in New York City: Analyzing the role of community-based organizations. *Urban Climate*, **40**, 101018. https://doi.org/10.1016/j.uclim.2021.101018

228. CBO, 2019: Expected Costs of Damage from Hurricane Winds and Storm-Related Flooding. Congressional Budget Office. https://www.cbo.gov/publication/55019

229. IPCC, 2023: Summary for policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Lee, H. and J. Romero, Eds. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 1-34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

230. Clayton, J., A. Devine, and R. Holtermans, 2021: Beyond building certification: The impact of environmental interventions on commercial real estate operations. *Energy Economics*, **93**, 105039. https://doi.org/10.1016/j.eneco.2020.105039

Fifth National Climate Assessment: Chapter 13

# Transportation

# Chapter 13. Transportation

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# Introduction

Transportation is fundamental to improving the quality of life in the United States and is a key enabler of economic and social activity for our communities. Transportation and mobility systems are more than a collection of modes (walking, cycling, cars, trucks, buses, trains, planes, and watercraft) to move people and goods in urban and rural environments. They are also a catalyst for change and offer an opportunity to reduce the impacts of a changing climate. Investments in transportation systems are linked to safety, environmental, social, and economic outcomes.

The transportation sector is experiencing rapid changes involving technologies, behaviors, workforce, supply chains, and logistics, all of which face increasing risks posed by climate hazards. Previous assessments highlighted risks arising from transportation investments that did not consider climate change. Challenges remain in managing the existing transportation system within a changing climate while planning for future transport needs with fewer negative impacts on the environment and communities. Historical, auto-centric land-use patterns make transitions to low-carbon transportation challenging (Ch. 12). These conditions necessitate that decision-makers be informed by the best data, science, and business practices, as well as by meaningful engagement with the most affected communities, to make sound short- and long-term transportation investments.

Our Nation's transportation system operates over a vast, unique geographic scale and serves a diverse set of users. It is a major emitter of greenhouse gas (GHG) emissions but is also vulnerable to climate hazards. Making transportation investments that are sustainable, climate-resilient, evidence-based, and equitable involves risk assessment and detailed dynamic analysis of long-term costs and impacts. Science and technology investments can enable rapid implementation of climate-informed decisions and analyses that incorporate a range of social, policy, finance, and engineering considerations toward improving mobility and increasing mobility options in urban and rural communities.

A lower-emissions transportation sector would mitigate GHG emissions, reduce the amount of carbon embedded in deployed materials, and promote cleaner air and healthier communities. However, such a transformation will involve trade-offs, with some negative impacts. Adaptation and mitigation strategies will differ by location. Inclusive decision-making and data-informed processes will help ensure that such impacts are not borne disproportionately by already overburdened communities.

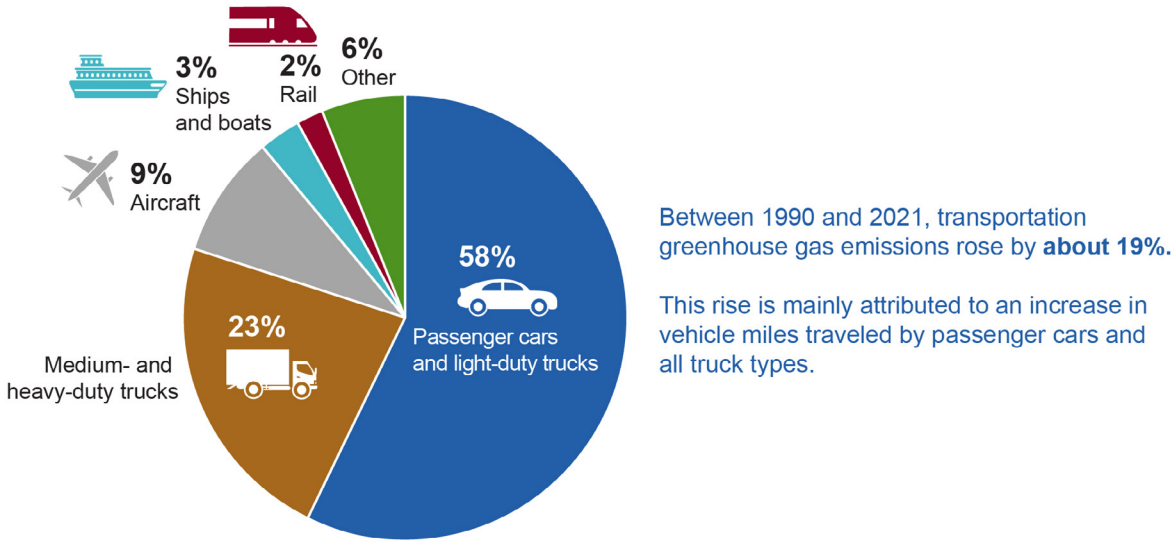
## Key Message 13.1

# Limiting Transportation Sector Emissions and Integrating Climate Projections Can Reduce Risks

The transportation sector is the largest source of greenhouse gas emissions in the United States, although transportation emissions sources are changing (*very high confidence*). The sector also faces increasing risk from climate-related extreme weather (*very high confidence*). Incorporating climate projections and adaptation and resilience best practices into transportation planning, design, operations, and maintenance can reduce such risks to the sector (*very high confidence*).

The transportation sector is the largest source of GHG emissions in the United States, accounting for 28.5% of total national emissions in 2021 (Figure 13.1). Carbon dioxide ($CO_2$) remains the dominant GHG in the sector.[1] Limiting global warming to 1.5°C (2.7°F) above preindustrial levels would require a path toward achieving net-zero GHG emissions by 2050.[2] Yet under current policy as of November 2021, projections of US transportation sector energy use and GHG emissions in 2050 are similar to current levels.[3] These projections assume continued increases in freight demand and in the number of miles traveled by vehicle per person, as well as existing powertrain trends. Other studies anticipate a more rapid switch to lower-GHG-emitting technologies resulting from declining costs of electric powertrains and other technologies, in part resulting from federal and state policy changes.[4,5,6,7]

### 2021 Greenhouse Gas Emissions from US Domestic Transportation by Mode




**Transportation remains the largest source of emissions in the US, with cars and light-duty trucks as the largest contributors.**

**Figure 13.1.** Greenhouse gas (GHG) emissions from the US domestic transportation sector rose by about 19% between 1990 and 2021 and remain the largest source of total national GHG emissions, with passenger cars and all types of trucks being the most significant contributors to the rise in transportation emissions. "Other" refers to buses, motorcycles, pipelines, and lubricants. Numbers do not add up to 100% due to rounding. Figure credit: Arizona State University and Texas Tech University. See figure metadata for additional contributors.

Multimodal planning is done at the Metropolitan Planning Organizations (MPO) and/or state level and guided by input from many stakeholders. It involves a comprehensive assessment of transportation needs and includes public involvement to address the needs of multiple users. This includes encouraging increased mass transit use and active modes of transportation such as walking or biking.[8,9,10,11,12] Roadmaps to meet 2050 net-zero emissions targets often include extensive efforts to replace passenger, transit, and freight vehicles with electric vehicles (EVs), which will raise electricity demand (Chs. 5, 32). Some state governments and nonprofits are encouraging the use of low-carbon fuels like hydrogen and biofuels for heavy-duty and hard-to-electrify vehicles, as well as for waterborne transportation modes and aircraft (Ch. 32). Although increasing efforts to electrify vehicles could reduce fossil fuel emissions, consideration must also be given to the challenges posed by this change, such as increased strain on energy grids; transitioning electricity generation from fossil fuels to renewable resources for the purpose of charging EVs; and repurposing, recycling, and safe disposal of EV batteries (KM 13.4; Ch. 17).

The COVID-19 pandemic briefly reduced GHG emissions from the transportation sector, but emissions have mainly rebounded to pre-pandemic levels (KM 13.3; Focus on Compound Events; Focus on COVID-19 and Climate Change).[13,14,15,16] Passenger cars currently contribute the most to transportation emissions; however, the share of emissions from heavy trucks and non-road sources (e.g., trains, airplanes, and ships) is expected to grow due to increasing demand (Ch. 10). Heavy trucks and non-road vehicles use fuels that are more polluting or could cause greater GHG emissions compared to passenger cars (e.g., diesel, jet fuel).[17,18] Expanding reliance on heavy-truck freight could offset any gains in fuel efficiency, resulting in a net increase in GHG emissions by 2050.[18] However, the costs of zero-emissions heavy-duty vehicles are changing rapidly.[19]

Similarly, the aviation sector could see a 50% increase in fuel use between 2020 and 2050 because of growing numbers of flights, even with advanced engine technologies.[17] For example, the Federal Government's Sustainable Aviation Fuel (SAF) Grand Challenge brings together the efforts of the Department of Energy, the Department of Transportation (DOT), the Department of Agriculture, and other federal agencies to reduce the cost, enhance the sustainability, and expand the production of SAF. This effort aims to produce SAF that achieves a minimum of a 50% reduction in life-cycle GHG emissions compared to conventional fuels and has a long-term goal of supplying sufficient SAF to meet 100% of aviation fuel demand by 2050.[20] Emissions-reductions efforts consider both $CO_2$ and non-$CO_2$ GHGs.[17]

Climate change and extreme weather events have a negative impact on transportation assets and human safety, often disproportionately affecting socially vulnerable populations (e.g., EPA 2021[21]). Examples of extreme weather events that caused significant transportation-related impacts in 2021 alone include debris flows and flooding after California wildfires, the winter storm in Texas, and Hurricanes Elsa, Florence, and Ida, which caused several deaths and billions of dollars in damages to the East Coast and Louisiana.[22]

Strategies that incorporate climate data and projected future impacts into analyses to support the full range of transportation processes (planning and management of assets over their life cycles, to include considerations of design, construction, operations and maintenance, and user needs) have the potential to reduce risks and costs over the long term (Ch. 31; Figures 31.5, 22.15; KM 12.2). Failure to adapt the transportation network to the impacts of climate change could be costly (e.g., Chinowsky et al. 2013;[23] Schweikert et al. 2015;[24] Neumann et al. 2021[25]). In particular, projected changes in temperature and precipitation, sea level rise, inland water level rise or fall, and storm surge are expected to significantly affect railroads, roads, ports, airports, and other transportation-related riverine and coastal properties in the United States (Ch. 12). Transportation planners are increasingly using analytical frameworks and tools to understand the vulnerabilities of their networks in pursuing a more resilient future (Table 13.1), although the focus on climate adaptation and resilience in transportation varies widely from region to region and state to state (KM 26.5).[26,27,28]

**Table 13.1. Climate and Transportation Vulnerabilities**

A selection of climate hazards and resulting transportation vulnerabilities are shown. Columns show selected climate hazards, and rows show individual transportation systems and the associated impacts on them. In some cases, possible adaptations to the vulnerabilities are included. Cells with few bullets represent the scarcity of research and not the lack of impact or vulnerability from climate hazards.

| Transport Mode | Extreme Temperatures | Storms | Drought | Fire |
|---|---|---|---|---|
| **Active transport (walking and biking)** | • Shift from active transport to vehicle or public transport[29]<br>• Adverse health impacts for walkers and cyclists (KM 15.1)[29] | • Shift from active transport to vehicle or public transport[30]<br>• Obstructions and infrastructure damage[30] | • Adverse health impacts for walkers and cyclists due to degraded air quality[31] | • Shift from active transport to vehicle or public transport[32]<br>• Reduced active transport due to short- and long-term health impairments[32] |
| **Aviation** | • Runway damage from heat and thawing permafrost[33,34]<br>• Altered flight schedules[35]<br>• Increased insect activity and chance of bird strikes[36,37,38] | • Coastal airport water intrusion[34,39] | • Soil subsidence[40]<br>• Increased dust storm risk[41] | • Increased risk of flooding due to loss of ground cover vegetation[42] |
| **Roadways** | • Cracking, buckling, and rutting from heat and permafrost thaw[34,40]<br>• Unsafe working conditions (KM 15.1)[33]<br>• Increased maintenance frequency[43,44,45] | • Damage from flooding, erosion, saturated soil, and sea level rise (Ch. 9)[34,40,43]<br>• Increased risk of landslides[43]<br>• Reduced life cycle from repeated runoff events[46]<br>• Travel lanes and bus routes blocked or rerouted due to flooding[28] | • Reduced pavement integrity due to subsidence, collapsible soils, and increased groundwater pumping[40,43]<br>• Reduced slope stability due to decreased roadside seeding uptake[47]<br>• Emergency bridge maintenance[48]<br>• Reduced visibility and increased closures from dust storms[41] | • Road closures and reduced visibility[40]<br>• Obstructions and debris flows (KM 6.1)[49]<br>• Increased chance of runoff[26,43]<br>• Reduced slope stability due to burn scar[50] |
| **Rail** | • Buckling of rails (KM 5.1)[34,40]<br>• Reduced train speeds[51]<br>• Catenary line sag[52] | • Flooding of bridges, tunnels, and low-lying rails[33,34]<br>• Damage from landslides[52] | • Changes in soil stability affecting track geometry and integrity[53] | • Damaged equipment[54]<br>• System disruption and rerouting[54] |
| **Pipelines** | • Structural damage due to permafrost thaw (KM 5.1)[55] | • Overloaded drainage systems[40]<br>• Pipeline shifting, exposure, and fracture due to heavy precipitation[34] | • Broken pipelines due to ground subsidence[34] | • Fire-induced toxicity in plastic water systems[56]<br>• Weakened pipelines due to increased runoff and debris flows[57] |
| **Waterborne** | • Reduced problems with ice accumulation and increased access to ports (Ch. 10)[34]<br>• Longer shipping seasons[34] | • Port damage due to increased storm surges and tides[34]<br>• River flooding[34] | • Reduced vessel carrying capacity due to lower water levels[34]<br>• Disrupted river transport due to inconsistent river flows (Chs. 22, 24)[33,34] | • Disruption of port operations due to electricity and supply chain disturbances[58,59] |

Tools and guidelines help organizations plan for the impacts of climate change, although individual agencies must still take the initiative to use them and challenge existing planning assumptions. Examples include the Federal Highway Administration (FHWA) Vulnerability Assessment and Adaptation Framework,[27] which can help transportation agencies assess their infrastructure's vulnerability to extreme weather and climate impacts. Another is the US DOT's Vulnerability Assessment Scoring Tool,[60] designed to help transportation planners conduct a quantitative, indicator-based screening of transportation system vulnerabilities to climate stressors, such as sea level rise, changes in precipitation, and higher temperatures. A 2021 study by the Transportation Research Board provided a risk-based decision support framework to inform quantitative methods for measuring resilience benefits.[61] Additional research could help model asset deterioration and vulnerability. However, Colorado DOT and Utah DOT pilot studies followed similar risk-based frameworks.[61]

The FHWA has deployed multiple climate-resilience efforts, including the Resilience and Durability to Extreme Weather Pilot Program, to partner with state departments of transportation, metropolitan planning organizations, and others, with the goal of evaluating the vulnerability of regional transportation assets to extreme weather events.[62] The Houston–Galveston Metropolitan Planning Organization participated in this pilot program and found that 13% of freeway miles and 12% of major road miles were highly vulnerable to flooding, storm surge, and sea level rise.[63]

The FHWA pilot program also included the three-county Tampa Bay region in Florida—one of the country's most inundation-vulnerable areas, with frequent storms and persistent flooding. The Hillsborough County Metropolitan Planning Organization found that when factoring in near-future projected sea level rise, 25% of major roads in the region could be impacted in a Category 3 hurricane.[64]

Several state departments of transportation have used some or parts of these frameworks to perform detailed vulnerability assessments and to understand the condition of their assets and risks from climate threats. These efforts may also be driven by state legislation, such as in California and New York,[65,66] by bottom-up approaches at individual state and local agencies. The California Department of Transportation (Caltrans) found that 20% of bridges, 19% of large culverts, 20% of small culverts, and 18% of roadway segments assessed and managed by Caltrans were rated in the highest risk category. This indicates that a large proportion of Caltrans infrastructure is at risk of damage or destruction due to increased storm surge, extreme floods, cliff erosion, extreme temperatures, and effects of wildfires.[43,67,68,69,70,71,72,73,74,75,76,77,78] California has recently mapped coastal transportation infrastructure vulnerable to 3 feet of sea level rise in Los Angeles and San Francisco and is considering a range of adaptation strategies, including nature-based solutions (Chs. 9, 28). Similar efforts have been completed by other states (including Washington, Tennessee, and Maryland) and subnational authorities.

Many agencies and organizations across the Nation have also initiated efforts to address the impacts of climate on a variety of transportation systems. While many of these are still in the initial stages of development, opportunities exist to improve on lessons state and local agencies have learned from the pilot programs at the local level (Ch. 12).[17,28,79]

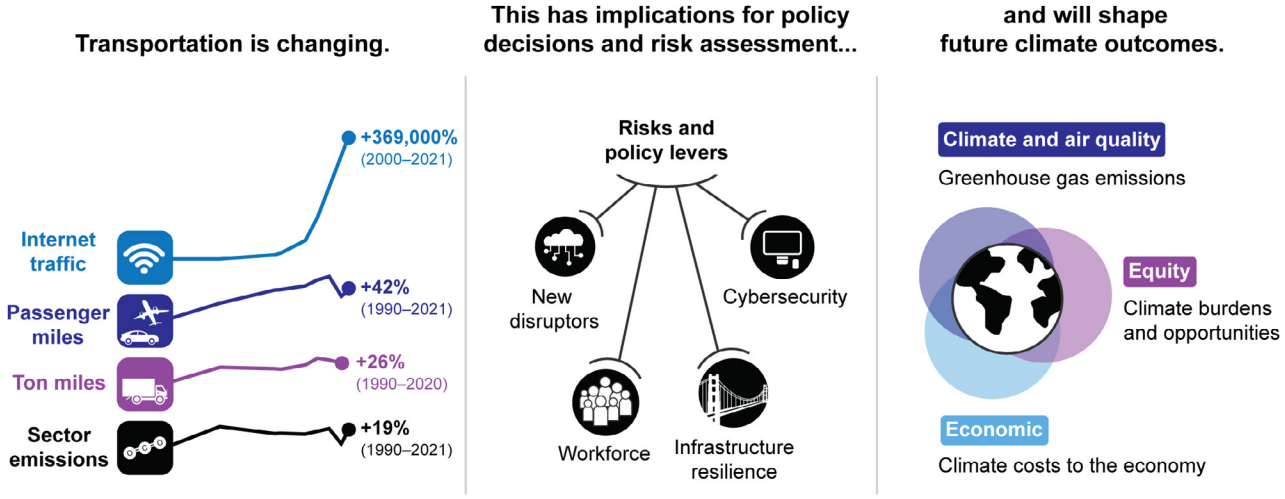
## Key Message 13.2

# Climate Change Combined with Other Disruptors Requires New Frameworks and Competencies

Climate action creates an opportunity to address concurrent disruptors, including cyber-technology integration, challenges with the condition of existing assets, and a changing workforce (*medium confidence*). Climate change has accelerated a transition to the use of more advanced approaches, including updated technologies, tools, and best practices (*high confidence*). Further recruitment and training of the sector's workforce is needed to effectively address these fundamental challenges (*high confidence*).

Moving toward a decarbonized, climate-adapted, and resilient transportation system can be more than simply a response to the climate crisis. The 21st-century transportation sector is undergoing rapid transformation. The integration of cyber-technology and advances in autonomous and connected vehicles are changing the nature of what transportation systems are and how they operate. Transportation's future is a complex, integrated, and dynamically shifting landscape marked by considerable uncertainty.[80] It faces unprecedented challenges from several sources: COVID-19; the growth of new technologies, business models, and opportunities; a massive shift to electrification; a changing logistics sector;[81,82] and significant workforce, diversity, and inclusion challenges. Cyber-vulnerabilities pose a profound challenge to the transportation industry[83,84,85] and communities, as well as national security risks. Figure 13.2 illustrates the complex relationship between the transportation sector, policy decisions and risk assessment, and future climate outcomes. Transportation system decisions made today have long-term implications for GHG emissions and climate adaptation. New tools and training have the potential to help navigate climate adaptation and disruption.

### Transportation Futures

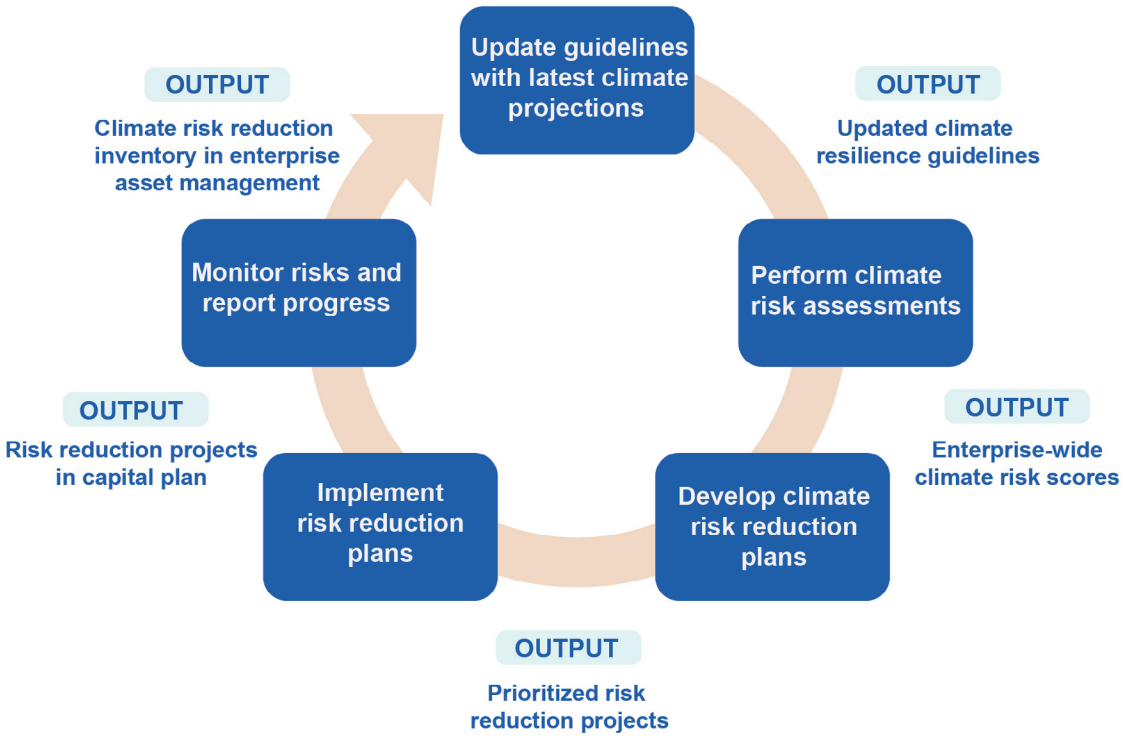



**A shifting transportation landscape, and how we respond to it, will determine future climate outcomes.**

**Figure 13.2.** The ways people, goods, and services travel have changed since 1990, especially with the dramatic rise of internet traffic. These changes create new challenges, such as cybersecurity impacts, and, coupled with workforce and infrastructure resilience challenges, are increasing the policy decisions in transportation. These decisions will shape future climate outcomes. Figure credit: Open Society Foundations, Introducing Youth to American Infrastructure Inc., NOAA NCEI, and CISESS NC.

Frameworks are emerging to help decision-makers incorporate climate uncertainty into infrastructure planning.[86] Using available data and tools provided by technological advancements in other sectors such as computing, sensors, cyber-technology, and statistics, public agencies and private companies are creating greater awareness and, in many cases, taking action to address the uncertainty brought about by climate change on the expected use and lifespan of transportation systems and on the design, construction, operations, and maintenance of transportation-related infrastructure (Figure 13.3).

## Resilience Planning Cycle




**Improving transportation resilience requires an iterative approach.**

**Figure 13.3.** This concept demonstrates a potential iterative approach to planning, investing, and building for climate resilience in the transportation sector, starting with 1) integration of updated climate projections into guidelines and workflows and proceeding to 2) assessment of climate change–related risks, 3) prioritization of climate risk-mitigation investments and strategies, 4) implementation of prioritized strategies, and 5) ongoing tracking and reporting of progress, culminating with updates to enterprise asset management (EAM) data—the foundation for the next resilience cycle. This process is underpinned by a strong climate resilience policy. This approach is designed to ensure that the pursuit of resilience is ongoing, adaptable, and both immediately relevant and future focused. Figure credit: Port Authority of New York and New Jersey.

Integrating climate data into engineering science is an emerging practice.[26,87,88,89,90,91,92,93,94,95,96,97,98] Advances in tools used for the planning, design, and construction of transportation and infrastructure projects are further changing the state of the practice.[92,95,99,100,101,102,103] The results of multiple years of climate research are beginning to see their way into transportation capital programming and project execution. Adaptation planning is beginning to recognize the challenges and opportunities of concurrent disruptors. For example, by harnessing low-cost heat and air quality sensors and increasingly accessible communication networks, researchers are showing the capabilities of informing active mobility users of high-exposure locations.[104] Decision-makers faced with evacuating large groups of people from extreme events can consider EV or non-traditional fleets. There is an ongoing effort, for example, to use EVs for powering buildings during

outages.[105,106] Sensors that can detect climate hazards such as flooding and communicate risks to the public, or that can be integrated into existing intelligent transportation systems, are rapidly advancing.[107]

Planning for adaptation concurrently with other disruptors will also require novel workforce capabilities. The transportation sector faces a number of workforce-related challenges, including aging, high retirement rates, retention issues, and industry-wide shortages for specific essential jobs; persistent underrepresentation of women and people of color; career awareness and image challenges impacting the attraction and recruitment of new employees; and significant technological impacts requiring further training and education related to the wider adoption of electric vehicles, information technology/cybersecurity risks, and increasing advances in artificial intelligence, robotics, and autonomous and connected vehicles.[108] As more employees gain the skills to navigate climate hazards, the sector will be better positioned to build resilience.[27,109,110,111] The transportation sector can define the competencies needed for its future workforce and collaborate with educational programs (including universities, professional societies, and continuing education programs) to modernize training. Elevating human resources management as an important element of organizational risk and vulnerability assessment will help ensure that workforce development and readiness are an integral part of climate mitigation and adaptation efforts (KMs 5.2, 7.3, 11.3, 16.2, 20.6; Ch. 29). The sector would further benefit from "K to gray"—a multipronged strategy that recognizes the importance of employee and workforce development and readiness at all levels and ages.[112]

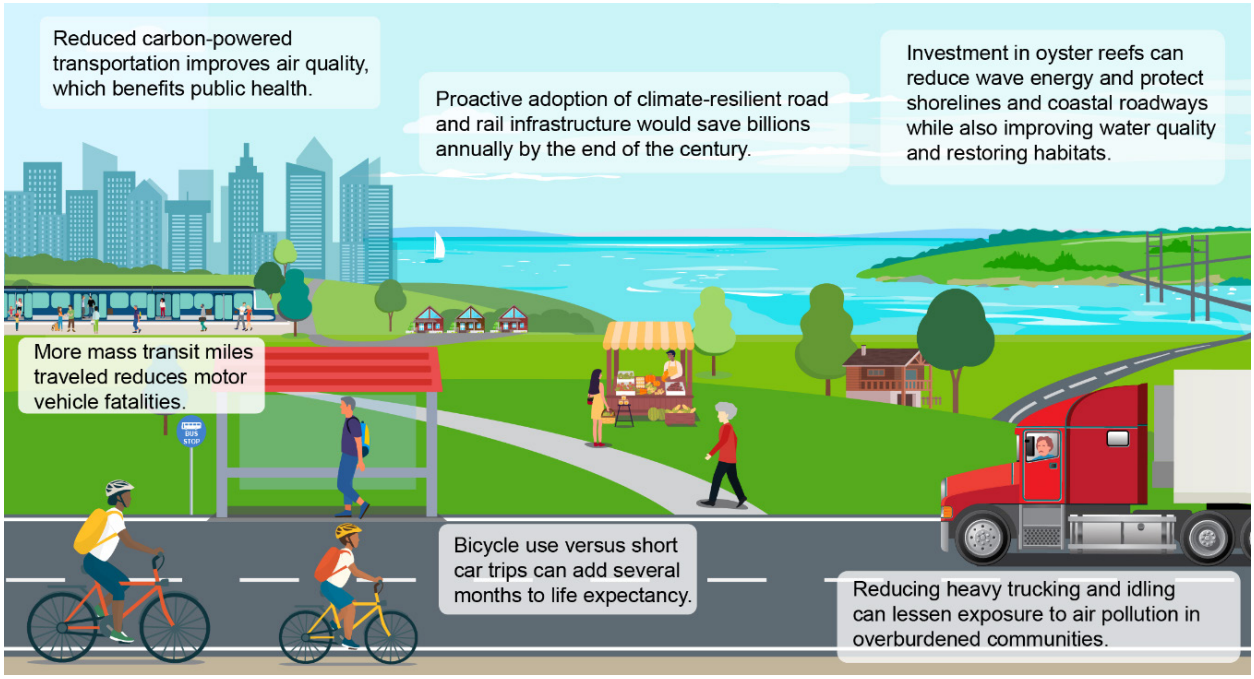
## Key Message 13.3

## Sustainable Transportation Would Produce Societal Benefits

A carbon-free, sustainable, and resilient transportation system would have co-benefits for human health, environmental justice, the natural environment, and economic development (*very high confidence*). When these co-benefits are considered, the benefits of greenhouse gas mitigation actions in the transportation sector far outweigh the costs (*high confidence*).

A carbon-free, sustainable, and resilient transportation system would have societal benefits beyond reduced climate change impacts, potentially leading to improvements in air quality, physical fitness, incidence of cardiovascular and respiratory disease, mental health, crash rates, noise pollution, social equity, ecosystems, biodiversity conservation, energy independence, and the economy.[113,114] When these co-benefits are considered, the benefits of GHG mitigation actions in the transportation sector far outweigh the costs (Figure 13.4).[115] Considering the impacts for different population subgroups can also ensure that these actions improve environmental, health, and social equity. These societal co-benefits would be particularly powerful in urban areas, where large numbers of people are experiencing elevated air pollution, health inequities, heat stress, traffic congestion, long commutes, and the negative health consequences of a sedentary lifestyle (Ch. 12). In contrast to the long-term and planetary-scale impacts of reducing GHGs from the transportation sector, these societal benefits would accrue immediately and locally, wherever the transportation emissions changes are implemented.

## Co-benefits of Mitigation and Resilience




**Decarbonizing transportation could save money and improve air quality, social equity, and the health of people and ecosystems.**

**Figure 13.4.** Integrating mitigation and resilience into transportation policies and planning at multiple scales leads to improved air quality, enhanced physical fitness from cycling, reduced environmental injustice as a result of decreases in heavy-duty trucking and idling, healthier ecosystems, and more economic opportunities. Figure credit: George Washington University and Jacobs.

The benefits of infrastructure and transportation resilience are also well documented and include increased reliability; lower costs to travelers, industry, and consumers, as well as to owners and operators of transportation infrastructure; improved safety and better health outcomes for workers and travelers; and the ability to support evacuations (KM 22.3).[116,117,118,119,120] However, significant resources are necessary to ensure the continued benefits and state of good repair of sustainable and climate-resilient transportation systems for all communities.[102]

Reducing GHGs in the transportation sector would also achieve co-benefits from improvements in air quality, climate and environmental equity, and physical fitness, as well as reduced incidence of cardiovascular disease, diabetes, and cancer (Figure 13.4; KM 12.3; Chs. 14, 24, 32)—all of which could counteract some climate impacts on human health (Ch. 15). Given the significantly high economic cost of air pollution in the United States, the monetary value of these benefits would be substantial.[121] Traffic-related emissions are a significant contributor to air pollutants, particularly fine particles ($PM_{2.5}$), ozone ($O_3$), and nitrogen dioxide ($NO_2$), all of which are associated with higher rates of illness and death.[122,123,124,125,126] In addition, emerging evidence suggests that exposure to elevated $CO_2$ levels indoors impacts cognitive function.[127] Reducing outdoor $CO_2$ emissions from the transportation sector could also reduce indoor $CO_2$ levels.[128]

Fuel efficiency, more stringent vehicle emissions standards, reduced passenger vehicle traffic, vehicle electrification, and mode switching to public transportation and walking or biking would result in co-benefits from improved air quality and better health. Modeling studies show that vehicle electrification reduces mortality related to $PM_{2.5}$ and $O_3$, even when considering increased emissions from additional energy demand.[129] However, increased energy use from demand for electricity, lithium mining, and potentially heavier vehicles can offset some of these air quality improvements when electricity generation

is from burning fossil fuels, highlighting the importance of transitioning to non-combustion electricity generation, such as from renewable energy sources (KM 13.4; Ch. 12).

COVID-19 lockdowns provided an unprecedented opportunity to examine how reduced passenger vehicle activity (and increased telework and bike use) affected $CO_2$ and air pollution. $CO_2$ emissions dropped by about 32% in April 2020 but rebounded to near normal by 2021, indicating that lifestyle changes (such as those experienced during the pandemic) must be coupled with transformative changes in transportation systems to reach GHG emissions-reduction targets (Focus on COVID-19 and Climate Change). In terms of air pollution, many cities experienced dramatic reductions in $NO_2$ pollution,[130,131] although impacts on $PM_{2.5}$ and $O_3$ were much more variable and location dependent.[132] Because traffic-related air pollution is inequitably distributed within US cities,[131,133] moving toward a carbon-free transportation system would also advance environmental and health equity. For example, air pollution inequity would be reduced through vehicle electrification, improved fuel efficiency, and structural actions to reduce vehicle-miles traveled for moving people and goods, such as changing the design of cities and increasing reliance on emissions-lowering modes, increasing public transportation use, and moving freight by rail rather than by road (Ch. 12). Walking or cycling instead of driving improves physical fitness and overall health,[115,134,135,136] and steps could be taken to ensure that safe access to these active transportation modes is available equitably across social groups. Active transportation and more time in natural environments also have mental health benefits, including improved cognitive function and well-being.[137] Reduced vehicle traffic also leads to fewer crashes and injuries.[115]

In recent years, several decision support tools have been developed to quantify and value the multiple benefits of actions that reduce transportation GHG emissions, including the Integrated Transport and Health Impact Model[138] and the Health Economic Assessment Tool for walking and cycling.[139] Integrating co-benefits into transportation policies and planning at multiple scales (e.g., neighborhood, urban, national) can create additional appeal for reducing transportation-sector GHG emissions for both decision-makers and the public. Key Messages 13.1 and 13.2 provide context on how to consider uncertainties in these decisions.

## Key Message 13.4

## Equitable Distribution of Transportation Trade-Offs and Benefits Requires Community Involvement

Although implementing adaptation and mitigation measures in the transportation sector will produce essential benefits and co-benefits, including addressing existing inequities, additional consideration is needed to avoid or reduce potential adverse consequences associated with these measures (*high confidence*). Moving toward climate resilience and environmental justice requires that these considerations, as well as current and historic inequities, be assessed through transparent and inclusive processes in order to provide equitable protection from environmental and health hazards and equitable access to transportation benefits (high confidence).

The need for climate mitigation and adaptation has created an opportunity to rethink transportation systems and land use at all levels. Still, such transformations (or decisions to maintain the status quo) may include some risks, with benefits sometimes accompanied by adverse or uncertain impacts (KM 13.2; Ch. 12). Political and policy actions in the US are generally based on compromise among an array of interests, which

may lead to trade-offs that fall short of idealized climate mitigation or adaptation actions. Moving toward equitable climate resilience and environmental justice via a just transition requires that consideration of such trade-offs be addressed through the full participation of relevant communities (Chs. 16, 31; KM 22.3).[140] Environmental justice also requires that trade-offs be managed in ways that address community self-determination,[141,142] as well as the needs of communities that are affected by transportation infrastructure and the impacts of the existing built environment or that currently lack reliable, sustainable, and affordable transportation services (Figure 13.5; Chs. 11, 17).[106,143,144]

Adopting alternative energy sources to reduce transportation emissions from fossil fuels has enormous potential for direct GHG and air pollution reduction, as well as opportunities for a just transition, but also includes potential risks or trade-offs. For example, battery production for EVs is mineral-intensive, requiring large quantities of lithium, nickel, copper, tantalum, and other minerals. Mining these raw materials may result in environmental degradation, public health harms, or displacement of nearby communities, as well as cultural impacts, including loss of sacred spaces.[145,146] Potential risks associated with adopting alternative energy sources should be considered in the context of current trade-offs related to existing energy sources, including the well-documented environmental and global climate change effects and adverse human health impacts resulting from the use of internal combustion–engine vehicles and fossil-energy power plants (KMs 5.2, 12.2). The siting of power-generation facilities, including utility-scale renewables, can have similar impacts. Experts have also noted that used batteries and electronic components pose the problem—and the opportunity—of repurposing, recycling, and disposal,[147] which researchers are currently working to address. Vehicle power source changes can also affect the distribution of road-user fees;[148] preferential registration fees are designed to signal preferences for one power source over another. Both of these revenue strategies could entail transportation funding trade-offs. The transition to zero-emissions vehicles may result in only localized air pollution reductions (KMs 13.3, 14.5).[149,150]

## Considerations of Equitable Climate Adaptation and GHG Mitigation from Transportation Systems

**Reducing emissions involves trade-offs that have implications for reliability, equity, and environmental quality.**

**Figure 13.5.** This figure shows many of the considerations where risks may arise as changes are made to transportation systems. Each tab on the figure represents a potential trade-off to all of the other factors shown. For example, changing transportation fuels or moving to electric drivetrains can decrease greenhouse gas and air pollutant emissions but may also affect transportation availability (which includes both geographical location and affordability) and reliability in underserved communities or in communities adapting to changing climates. Further, mining of raw materials for those technologies has the potential to damage ecosystems and cultural or sacred landscapes. Accordingly, decisions about climate mitigation and adaptation in transportation systems should be carefully considered through lenses of environmental justice and community self-determination. Figure credit: EPA and University of Idaho.

Climate adaptation actions entail consideration of trade-offs. For example, moving a coastal roadway inland to avoid sea level rise (i.e., managed retreat) may not allow for an immediate modal shift, but it may provide an opportunity to reconsider the size and capacity of the roadway and also allow for landscape restoration along the original alignment, as illustrated by the Highway A1A Redesign Project in Fort Lauderdale, Florida, and the Piedras Blancas Highway 1 Realignment project in San Luis Obispo, California (Ch. 9).[151,152]

For the freight transportation system, equitable distribution of trade-offs under a climate change framework will also require particular attention. In addition to turning over vehicles and equipment to lower-emissions or zero-emissions technologies, there are opportunities to obtain energy savings and emissions reductions by shifting freight from road transport to rail or water. Further infrastructure development will be necessary to make such mode shifting more viable.

Changing the geographical footprint of freight systems also brings up trade-offs. Inland port facilities can receive and manage cargo that has been unloaded from a seaport some distance away and transported via low-polluting transport modes (in terms of tailpipe and full-life-cycle air pollutant and GHG emissions, such as electric or hybrid locomotives or trucks) or highly efficient modes (energy use per cargo per mile, such as rail), or both, with the potential to boost system efficiency and reduce air pollutants and GHG emissions and reduce exposure to air pollutants in communities near seaports.[153] However, people living near such inland freight facilities could in turn experience increased traffic, air pollution, and environmental damage, creating or exacerbating environmental injustice. Emissions inventory methodologies can help to quantify these impacts and enable affected communities and decision-makers to develop emissions-reduction strategies from different activities and/or equipment types (Focus on Risks to Supply Chains).[154,155]

Trade-offs related to the freight workforce are also becoming clear. For example, independent truck owner-operators, who do not work for a larger employer and own their own trucks, may not have the resources to purchase and operate cleaner vehicles or have access to appropriate fueling or charging infrastructure.[156,157]

# Traceable Accounts

## *Process Description*

Selection of the author team considered a balance in gender, race, geography, and affiliation type. In addition, a holistic systems approach was considered essential in the development of this chapter. While transportation is the primary source of greenhouse gases and air pollution, there is a recognition that mitigating climate change impacts and developing transportation adaptation strategies have vital implications for other sectors. For these reasons, the authors were also selected for their expertise in the built environment and infrastructure, workforce development, education, funding and financing, public health, safety and security, customer experience, diversity and inclusion, and downscaled data analysis, as well as knowledge of global systems and resources. Special consideration was given to authors' understanding of perspectives from rural, urban poor, Arctic, and Pacific Islander communities; youth; and the Global South.

The author team was scheduled to meet every Wednesday throughout the Fifth National Climate Assessment (NCA5) process. During those meetings, the chapter lead (CL) facilitated meetings by going through the outcomes and milestones expected at every phase of the project, mitigated any specific process concerns, invited guest speakers such as Technical Support Unit (TSU) staff and technical contributors as necessary, and developed and followed up on milestones and expected outcomes. On certain weeks, meetings were not held, either to make time to complete specific tasks or for author team members to consult with TSU staff, or when a milestone or deliverable needed to be appraised within the chapter team or with other chapters teams. These weekly team meetings were also opportunities to build a consensus.

The author team was given subsections to work on and develop, but each subsection team member was free to work on or collaborate, as appropriate, with other subsection teams.

The CL and federal coordinating lead author (CLA) met with leadership from other chapters, taking note of their Key Messages (KMs). The CL provided an overview of these KMs to the Transportation chapter author team to help shape the development of each KM and its supporting narrative, figures, and tables (where appropriate). The CLA confirmed with CLAs from other chapters where statements made in the Transportation chapter could be reinforced by the assessments made by other chapters and vice versa.

The author team conducted a public meeting in February 2022, after the Zero Order Draft was submitted, with two plenaries and three breakout sessions. Input was received from the general public at these meetings. Additional stakeholder engagement was held for youth interested in participating in the NCA5 process. Transportation and other chapters made a presentation and joined breakout rooms where questions were answered. Additional comments on the Third Order Draft were received from the public and from the National Academies of Sciences, Engineering, and Medicine (NASEM).

These public and NASEM comments were assigned individually to chapter authors who could best provide a draft response. Draft responses were reviewed by the author team and finalized on consensus. The chapter's review editor provided feedback on these responses, and a final response was adopted. The chapter was revised according to the final responses to the public and NASEM comments.

## Key Message 13.1

# Limiting Transportation Sector Emissions and Integrating Climate Projections Can Reduce Risks

### Description of Evidence Base

There is significant and increasing evidence of the greenhouse gas (GHG) emissions from the transportation sector and how those emissions could change into the future. EPA's Inventory of US Greenhouse Gas Emissions and Sinks provides a year-by-year estimate of GHG emissions from the transportation sector.[1] Scenarios describing changes in transportation sector emissions into the future differ based on assumptions about technology, powertrain, demand, and other variables.[1,2,3,5,6] The literature often focuses on identifying a confluence of variables needed to meet GHG-reduction goals. Electric vehicle (EV) adoption, including the GHG intensity of charging, and fuel cell vehicle development have become rich areas of study.[7] The costs of decarbonizing heavy-duty vehicles are dropping, but increases in truck-miles could offset benefits.[18,19] Aviation forecasts often contrast fuel economy gains relative to changes in demand.[17]

Literature and evidence on the impacts of climate hazards on transportation infrastructures and operations are growing rapidly. The literature generally covers either the vulnerabilities of systems or the costs of adaptation.[23,40] Costs to implement adaptation and mitigation vary across the country and according to the scale of actions, are inconsistently tracked over the lifetime of a policy or program, and tend to be tracked only in each phase of the initiative. There is also a growing body of risk, vulnerability, and resilience frameworks for transportation systems, and no clear consensus has emerged on the precise steps needed to protect transportation systems against climate hazard–associated uncertainty.[61]

With respect to incorporating observed and projected changes in climate into the design criteria of infrastructure systems, there is a small but growing evidence base. Although applicable to transportation infrastructure, the majority of the work in this space relates to infrastructure more generally.

### Major Uncertainties and Research Gaps

The long-term outlook and extrapolation of trends in transportation GHG emissions, especially given supply chain shocks resulting from COVID-19, are highly uncertain.[15,16] While EV market shares are growing, they still represent a small fraction of the light-duty fleet and an even smaller fraction of the heavy-duty fleet.[7] How EV adoption and fuel cell vehicle development and adoption, in combination with other factors, result in future GHG emissions changes in the transportation sector is highly uncertain.

There is also uncertainty regarding whether and how incorporating new data, improved data, and climate projections into transportation sector decision-making leads to improved outcomes. Uncertain localized climate data, uncertainty in future climate, and uncertainty in applying legacy risk-based approaches under new climate paradigms result in an unclear picture of how new and enhanced data with new resilience frameworks translate into better decision-making.[40]

### Description of Confidence and Likelihood

There is *very high confidence* that the transportation sector is the most significant single-sector contributor to national greenhouse gas emissions. This is corroborated by extensively reviewed, studied, and verified data on vehicle travel and associated emissions. There is also *very high confidence* that the transportation sector faces increasing risk from climate-related extreme weather. Transportation systems are diverse and present everywhere in the US, meaning that they are exposed to all climate hazards. Aging assets and state-of-good-repair challenges contribute to this risk. There is *very high confidence* that transportation agencies and planning organizations understand potential climate impacts and are addressing them to varying

degrees by incorporating climate projections into planning, design, operations, and maintenance to reduce risks to the sector. Peer-reviewed articles and publicly available reports and documents support the stated confidence levels.

Specific to vulnerabilities and impacts, the author team recognizes that agencies may not release operational data and that, therefore, this information may not be publicly available, except in cases where such information would be useful to support gray literature. Those references were called out with a full understanding that data and statistics may have been reported without the full context of the source of the empirical information.

## Key Message 13.2

## Climate Change Combined with Other Disruptors Requires New Frameworks and Competencies

### Description of Evidence Base

This assessment is based on publicly available sources, including federal and state information; discussions with diverse subject-matter experts and technical contributors; and a focused literature scan, including some peer-reviewed sources. Although peer-reviewed literature broadly supports the notion that the transportation sector faces a variety of emerging, potentially disruptive changes,[80] few peer-reviewed sources exist that explicitly link coordination of those challenges (and solutions) to climate action. The acceleration of climate change–informed decision-making in the transportation sector is best demonstrated by the recent proliferation of frameworks and tools for this purpose,[27,86] but peer-reviewed literature also supports this claim.[99] Ample peer-reviewed and gray literature supports the discussion of emerging transportation workforce challenges[112] and the corresponding need to upskill and diversify the demographics of transportation workers to address these challenges.

### Major Uncertainties and Research Gaps

Key Message 13.2 focuses on potential opportunities and threats stemming from the convergence of a changing climate, emerging non-climate disruptors, and rapid, concurrent transformation of the transportation sector and its workforce—all of which compound uncertainty. In particular, the rate of adoption of EVs and the maturity and deployment of autonomous and connected vehicle technologies are moderately to highly uncertain. In addition, the transportation sector is not monolithic, potentially reducing the credibility of overarching claims or conclusions. Major differences exist across the widely varying transportation modes and regions of the United States, including notable divergences between urban, suburban, and rural environments; areas of relative wealth or poverty; and historically underrepresented and/or overburdened communities.

Notable research gaps include a relative lack of publicly available data of sufficient uniformity, granularity, and credibility (especially from subsectors dominated by private operators or where agency operational data are not publicly available), which complicates attempts to achieve data-informed decisions and monitor outcomes. Relatedly, there is currently little consensus on how sustainability and resilience, as well as climate change goals, progress, and outcomes, are reported in the sector.

Finally, peer-reviewed literature on the potential co-benefits (or disbenefits) of coordinating responses to climate-related challenges and non-climate disruptors is relatively scant, despite ample anecdotal evidence.

### Description of Confidence and Likelihood

Due to the lack of a strong foundation of peer-reviewed literature, the claim that climate action presents an opportunity to address emerging non-climate disruptors is assigned *medium confidence*, primarily rooted in gray literature and credible expert opinion. The well-documented, relatively recent proliferation of resources to support deliberate climate action in the sector yields a *high confidence* rating for the claim that approaches and tools are available and are being applied, with the caveat that little evidence exists that these tools produce actionable outputs or successful outcomes. There is *high confidence* that further recruitment and training is needed to ensure that the sector's workforce can succeed amid rapid climate and non-climate transformations. Sufficient data to support likelihood assessments are not readily available.

## Key Message 13.3

## Sustainable Transportation Would Produce Societal Benefits

### Description of Evidence Base

This assessment is based on peer-reviewed journal articles and publicly available reports that evaluate multiple impacts of actions taken in the transportation sector to mitigate carbon emissions and become more resilient to the effects of climate change. The evidence base for co-benefits comes from studies focusing on both the societal burden from the current transportation system and the societal benefits that would come from a less carbon-intensive and more climate-resilient transportation system. This evidence base covers transportation impacts on health via motor vehicle crashes, high air pollution and noise levels, heat island effects, and lack of green space and physical activity.[114] It also covers how transportation provides many jobs, which generate income and improve health.[114] These studies are multidisciplinary and vary in methods, including both quantitative and qualitative approaches.

Among the most studied consequences of our current transportation system are air quality and health impacts. A large body of literature developed over decades demonstrates that vehicle emissions contribute to poor air quality and a range of deleterious health outcomes, including premature mortality, cardiovascular disease, respiratory disease, and lung cancer.[122,123,126] Studies have also shown that policies that reduced emissions from the transportation sector, including through transitioning to zero-emissions vehicles, can reduce the incidence[124] and exacerbation of asthma.[125] Additional studies have explored potential air quality and health benefits of hypothetical policies, accounting for both reduced tailpipe air pollution emissions and potentially increased emissions from fossil fuel–based electricity generation.[129]

While fewer studies focus on the other pathways of improvements that would come from different actions that could be taken to decarbonize and improve resilience of the transportation system, a growing body of literature assesses benefits for physical fitness,[134,135] reduced crashes and injuries,[115] improved health for transportation workers,[117] and environmental justice and health equity.[131] Fewer studies have taken a holistic view of many societal benefits that would accrue simultaneously, which is necessary to comprehensively evaluate different actions that could be taken, from tailpipe emission and fuel efficiency standards to restructuring the transportation system in cities to encourage public transportation and walking and cycling. However, studies find that these potential co-benefits can motivate public, private, and financial actions to mitigate greenhouse gases[113] and can outweigh the costs of taking action.[115]

### Major Uncertainties and Research Gaps

Co-benefits assessments are often highly context-specific, limiting the ability to extrapolate the results to different geographical areas, populations, and actions, including policies, programs, and projects. Costs to implement adaptation and mitigation vary across the country and are often tracked only in individual phases

of the initiative. There is a lack of research verifying the actual costs and benefits of programs and projects that have already been implemented to reduce transportation-related carbon emissions and improve the resilience of the transportation system. Some national calculators perform such cost–benefit analysis. These include the Integrated Transport and Health Impact Model[138] and the Health Economic Assessment Tool for walking and cycling.[139] However, there is still a gap in the consistency of the true meaning of the quantified outcomes relative to the transportation sector, the area where those programs or projects are created, and how those outcomes could be integrated for an accurate measure of benefits beyond project-level co-benefits. An important gap lies in more holistic life-cycle tracking of the costs over the life of the asset or program.

There is also a lack of research that assesses the distributional benefits of transportation mitigation and resilience policies, programs, and projects on different population subgroups and overburdened communities. For example, studies find that transportation tailpipe emissions contribute to racial and socio-economic disparities in air pollution levels; however, several key technical limitations make it challenging to fully characterize which communities could experience the greatest improvements in air quality and associated health benefits from national, state, and local policies or other measures that reduce transportation tailpipe emissions. Similarly, there is a need to consider the effectiveness of different mitigation and adaptation actions for different locations and populations, given inequities in safe, accessible, and reliable transportation options.

### Description of Confidence and Likelihood

There is *very high confidence* that policies, programs, and projects to reduce transportation-related carbon emissions and transition to a more resilient transportation system would lead to environmental, health, and economic co-benefits. This conclusion is based on the strength and consistency of the peer-reviewed literature and publicly available reports documenting the many societal improvements that would come from actions to decarbonize the transportation sector and make it more resilient to climate change. Despite the research gaps limiting our understanding of the co-benefits of specific mitigation and adaptation actions taken in specific locations and of the impacts of these actions on environmental, health, and social equity, the large and multidisciplinary body of literature finding that mitigation and improved resilience results in many societal co-benefits provides sufficient evidence to draw this conclusion.

There is *high confidence* that when these co-benefits are considered, the benefits of GHG mitigation actions in the transportation sector far outweigh the costs. Some evidence suggests that potential co-benefits outweigh the costs of taking action, particularly when the action results in reduced human mortality. However, the value of co-benefits and costs are highly context-specific and dependent on the type, scale, and design of the action being considered or taken.

## Key Message 13.4

## Equitable Distribution of Transportation Trade-Offs and Benefits Requires Community Involvement

### Description of Evidence Base

This assessment is based on peer-reviewed journal articles and government reports. The environmental and societal impacts of various transportation technologies and systems are well documented.[146] Sources and specific locations of raw materials for electrified transportation technologies are also well known, and the environmental and community impacts of mining and extraction operations have been deeply analyzed in many specific locations.[145] The trade-offs of climate change mitigation and adaptation in the freight

transportation sector are also well known, as governments, freight operators, and cargo owners are concurrently implementing and analyzing actions in those areas, and planning for the future, with extensive documentation of those processes.[153] The benefits of community engagement in government processes, including in the transportation sector, are also extensively documented in the literature.[140] There is also an emerging best practice to include equity and inclusion criteria in the development and implementation of transportation strategies.[143,144]

## Major Uncertainties and Research Gaps

Projections of the specific life-cycle environmental and societal impacts of not-yet-implemented transportation technologies and systems are necessarily uncertain. Specifically, impacts of mineral mining for EV battery raw materials have been extensively analyzed for sites within the lithium triangle of South America; however, large-scale mining of such materials is less prevalent in the US, so fewer analyses of these impacts have been performed.[145] There is also a lack of research analyzing the environmental and GHG benefits from freight transportation mode shifts.

## Description of Confidence and Likelihood

There is *high confidence* that significant trade-offs will occur in implementing adaptation and mitigation measures in the transportation sector, based on the strength and consistency of the peer-reviewed literature and publicly available reports regarding contemporary environmental and energy transitions. There is *high confidence* that environmental justice requires transparent and inclusive processes, as the literature and government policy[141] clearly indicate that equal access to decision-making processes is a key element of environmental justice.

# References


1. EPA, 2023: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021. EPA 430-R-23-002. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021

2. IPCC, 2022: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926

3. EIA, 2022: Annual Energy Outlook 2022. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/outlooks/aeo/narrative/introduction/sub-topic-02.php

4. Bertrand, S., 2022: How the Inflation Reduction Act and Bipartisan Infrastructure Law Work Together to Advance Climate Action. Environmental and Energy Study Institute. https://www.eesi.org/articles/view/how-the-inflation-reduction-act-and-bipartisan-infrastructure-law-work-together-to-advance-climate-action

5. CARB, 2022: Proposed Advanced Clean Cars II Regulations: All New Passenger Vehicles Sold in California to be Zero Emissions by 2035. California Environmental Protection Agency, California Air Resources Board. https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/advanced-clean-cars-ii

6. DOE, 2020: SMART Mobility: Multi-Modal Freight Capstone Report. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/sites/prod/files/2020/08/f77/SMART-MMF_Capstone_08.03.20.pdf

7. National Academies of Sciences, Engineering, and Medicine, 2021: *Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy—2025–2035*. The National Academies Press, Washington, DC, 468 pp. https://doi.org/10.17226/26092

8. FHWA, 2018: The Transportation Planning Process Briefing Book. FHWA-HEP-18-015. U.S. Department of Transportation, Federal Highway Administration. https://www.fhwa.dot.gov/planning/publications/briefing_book/index.cfm

9. IEA, 2021: Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency, Paris, France. https://www.iea.org/reports/net-zero-by-2050

10. Larson, E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, E. Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan, 2021: Final Report Summary—Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Princeton University, Princeton, NJ. https://netzeroamerica.princeton.edu/the-report

11. Sperling, D., Lew Fulton, and V. Arroyo, 2020: Ch. 5.2. Accelerating deep decarbonization in the U.S. transportation sector. In: *Zero Carbon Action Plan* 188. Sustainable Development Solutions Network, New York, 188–210. https://scholarship.law.georgetown.edu/facpub/2318/

12. Baek, Y., T. Boettner, R. Cleetus, S. Clemmer, C. Esquivia-Zapata, C. Farley, B. Isaac, J. Koeppel, J. Martin, J. McNamara, C. Pinto de Moura, S. Sathia, S. Sattler, M. Unseld, and S. Welton, 2021: A Transformative Climate Action Framework: Putting People at the Center of Our Nation's Clean Energy Transition. Union of Concerned Scientists, Cambridge, MA, 25 pp. https://www.ucsusa.org/resources/clean-energy-transformation

13. BTS, 2022: On Earth Day 2022, BTS Looks at Public Transportation Ridership and Tailpipe Emissions. U.S. Department of Transportation, Bureau of Transportation Statistics. https://www.bts.gov/data-spotlight/earth-day-2022-bts-looks-public-transportation-ridership-and-tailpipe-emissions

14. Kumar, A., P. Singh, P. Raizada, and C.M. Hussain, 2022: Impact of COVID-19 on greenhouse gases emissions: A critical review. *Science of The Total Environment*, **806**, 150349. https://doi.org/10.1016/j.scitotenv.2021.150349

15. Tollefson, J., 2021: Carbon emissions rapidly rebounded following COVID pandemic dip. *Nature*. https://doi.org/10.1038/d41586-021-03036-x

16. Tollefson, J., 2021: COVID curbed carbon emissions in 2020—But not by much. *Nature*, **589** (7842), 343. https://doi.org/10.1038/d41586-021-00090-3

17. FAA, 2021: United States 2021 Aviation Climate Action Plan. Federal Aviation Administration. https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

18. ITF, 2018: Is Low-Carbon Road Freight Possible? International Transport Forum, 5 pp. https://www.itf-oecd.org/sites/default/files/docs/cop24-road-freight.pdf

19. Ledna, C., M. Muratori, A. Yip, P. Jadun, and C. Hoehne, 2022: Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis. U.S. Department of Energy, National Renewable Energy Laboratory, 69 pp. https://www.nrel.gov/docs/fy22osti/82081.pdf

20. DOE, DOT, USDA, and EPA, 2022: SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel. U.S. Department of Energy, U.S. Department of Transportation, U.S. Department of Agriculture, and U.S. Environmental Protection Agency. https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf

21. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

22. NCEI, 2022: U.S. Billion-Dollar Weather and Climate Disasters: Disaster and Risk Mapping. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncdc.noaa.gov/billions/mapping

23. Chinowsky, P.S., J.C. Price, and J.E. Neumann, 2013: Assessment of climate change adaptation costs for the U.S. road network. *Global Environmental Change*, **23** (4), 764–773. https://doi.org/10.1016/j.gloenvcha.2013.03.004

24. Schweikert, A., X. Espinet, S. Goldstein, and P. Chinowsky, 2015: Resilience versus risk: Assessing cost of climate change adaptation to California's transportation system and the city of Sacramento, California. *Transportation Research Record*, **2532** (1), 13–20. https://doi.org/10.3141/2532-02

25. Neumann, J.E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich, 2021: Climate effects on US infrastructure: The economics of adaptation for rail, roads, and coastal development. *Climatic Change*, **167** (3), 44. https://doi.org/10.1007/s10584-021-03179-w

26. FHWA, 2017: Synthesis of Approaches for Addressing Resilience in Project Development. FHWA-HEP-17-082. U.S. Department of Transportation, Federal Highway Administration. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/synthesis/fhwahep17082.pdf

27. FHWA, 2017: Vulnerability Assessment and Adaptation Framework, 3rd Edition. FHWA-HEP-18-020. U.S. Department of Transportation, Federal Highway Administration. https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/

28. FTA, 2014: Transit and Climate Change Adaptation: Synthesis of FTA-Funded Pilot Projects. FTA Report No. 0069. U.S. Department of Transportation, Federal Transit Administration, Washington, DC. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_Report_No._0069_0.pdf

29. Karner, A., D.M. Hondula, and J.K. Vanos, 2015: Heat exposure during non-motorized travel: Implications for transportation policy under climate change. *Journal of Transport & Health*, **2** (4), 451–459. https://doi.org/10.1016/j.jth.2015.10.001

30. Doubleday, A., Y. Choe, S. Miles, and N.A. Errett, 2019: Daily bicycle and pedestrian activity as an indicator of disaster recovery: A Hurricane Harvey case study. *International Journal of Environmental Research and Public Health*, **16** (16), 2836. https://doi.org/10.3390/ijerph16162836

31. NCEH, 2022: Drought and Your Health. Centers for Disease Control and Prevention, National Center for Environmental Health. https://www.cdc.gov/nceh/features/drought/index.html

32. Doubleday, A., Y. Choe, T.M. Busch Isaksen, and N.A. Errett, 2021: Urban bike and pedestrian activity impacts from wildfire smoke events in Seattle, WA. *Journal of Transport & Health*, **21**, 101033. https://doi.org/10.1016/j.jth.2021.101033

33. EPA, 2016: Climate Impacts on Transportation. U.S. Environmental Protection Agency. https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-transportation

34. Transportation Research Board and National Research Council, 2008: *Potential Impacts of Climate Change on U.S. Transportation: Special Report 290*. The National Academies Press, Washington, DC, 296 pp. https://doi.org/10.17226/12179

35. Carpenter, B.T., 2019: An overview and analysis of the impacts of extreme heat on the aviation industry. *Pursuit - The Journal of Undergraduate Research at The University of Tennessee*, **9** (1), 2. https://trace.tennessee.edu/pursuit/vol9/iss1/2

36. Burger, J., 1983: Bird control at airports. *Environmental Conservation*, **10** (2), 115–124. http://www.jstor.org/stable/44517477

37. National Academies of Sciences, Engineering, and Medicine, 2015: *Climate Change Adaptation Planning: Risk Assessment for Airports*. The National Academies Press, Washington, DC. https://doi.org/10.17226/23461

38. National Academies of Sciences, Engineering, and Medicine, 2018: *Using Existing Airport Management Systems to Manage Climate Risk*. The National Academies Press, Washington, DC, 64 pp. https://doi.org/10.17226/25327

39. Lindbergh, S., Y. Ju, Y. He, J. Radke, and J. Rakas, 2022: Cross-sectoral and multiscalar exposure assessment to advance climate adaptation policy: The case of future coastal flooding of California's airports. *Climate Risk Management*, **38**, 100462. https://doi.org/10.1016/j.crm.2022.100462

40. Markolf, S.A., C. Hoehne, A. Fraser, M.V. Chester, and B.S. Underwood, 2019: Transportation resilience to climate change and extreme weather events—Beyond risk and robustness. *Transport Policy*, **74**, 174–186. https://doi.org/10.1016/j.tranpol.2018.11.003

41. Middleton, N., P. Tozer, and B. Tozer, 2019: Sand and dust storms: Underrated natural hazards. *Disasters*, **43** (2), 390–409. https://doi.org/10.1111/disa.12320

42. Phillips, C. and K. Dahl, 2022: Fire and Water in the Western United States: How Worsening Wildfires Threaten Water Resources in the West. Union of Concerned Scientists, Cambridge, MA. https://www.ucsusa.org/resources/wildfire-water-western-united-states

43. Caltrans, 2019: 2019 Climate Change Vulnerability Assessments. State of California, California Department of Transportation. https://dot.ca.gov/programs/transportation-planning/division-of-transportation-planning/air-quality-and-climate-change/2019-climate-change-vulnerability-assessments

44. Mallick, R.B., M.J. Radzicki, J.S. Daniel, and J.M. Jacobs, 2014: Use of system dynamics to understand long-term impact of climate change on pavement performance and maintenance cost. *Transportation Research Record*, **2455** (1), 1–9. https://doi.org/10.3141/2455-01

45. Underwood, B.S., Z. Guido, P. Gudipudi, and Y. Feinberg, 2017: Increased costs to US pavement infrastructure from future temperature rise. *Nature Climate Change*, **7**, 704. https://doi.org/10.1038/nclimate3390

46. Union of Concerned Scientists, 2019: Testimony of Dr. Kristina Dahl, "The Need for Resilience: Preparing American's Transportation Infrastructure for Climate Change". Union of Concerned Scientists, 8 pp. https://www.ucsusa.org/sites/default/files/attach/2019/07/dahl-written-testimony-transportation-infrastructure-5-21-19.pdf

47. MNDOT, 2022: Roadside Vegetation Management. Minnesota Department of Transportation, St. Paul, MN. https://www.dot.state.mn.us/roadsides/vegetation/

48. Mendez, B., 2022: Staying safe in the heat wave: How we're protecting city infrastructure and reminders for safe and healthy travel. Seattle Department of Transportation Blog, Seattle, WA. https://sdotblog.seattle.gov/2022/07/25/staying-safe-in-the-heat-wave-how-were-protecting-city-infrastructure-and-reminders-for-safe-and-healthy-travelnbsp/

49. California Water Science Center, 2018: Post-Fire Flooding and Debris Flow. U.S. Geological Survey. https://ca.water.usgs.gov/wildfires/wildfires-debris-flow.html

50. Chester, M.V. and R. Li, 2020: Vulnerability of California Roadways to Post-Wildfire Debris Flow. Report No. UC-ITS-2020-38. University of California, Institute of Transportation Studies. https://doi.org/10.17610/t60w35

51. Rowan, E., C. Evans, M. Riley-Gilbert, R. Hyman, R. Kafalenos, B. Beucler, B. Rodehorst, A. Choate, and P. Schultz, 2013: Assessing the sensitivity of transportation assets to extreme weather events and climate change. *Transportation Research Record*, **2326** (1), 16–23. https://doi.org/10.3141/2326-03

52. Los Angeles County Metropolitan Transportation Authority, 2019: Metro Climate Action and Adaptation Plan. Environmental Compliance and Sustainability Department. https://libraryarchives.metro.net/dpgtl/sustainability/2019-Climate_Action_Plan.pdf

53. Rossetti, M.A., 2003: Potential Impacts of Climate Change on Railroads. U.S. Department of Transportation, Volpe Center, 13 pp. https://www.transportation.gov/sites/dot.gov/files/docs/rossetti_CC_Impact_Railroads.pdf

54. Chinowsky, P., J. Helman, S. Gulati, J. Neumann, and J. Martinich, 2019: Impacts of climate change on operation of the US rail network. *Transport Policy*, **75**, 183–191. https://doi.org/10.1016/j.tranpol.2017.05.007

55. Williams, P.J., M. Wallis, P. Wadhams, J.A. Dowdeswell, and A.N. Schofield, 1995: Permafrost and climate change: Geotechnical implications. *Philosophical Transactions of the Royal Society of London. Series A: Physical and Engineering Sciences*, **352** (1699), 347–358. https://doi.org/10.1098/rsta.1995.0075

56. Isaacson, K.P., C.R. Proctor, Q.E. Wang, E.Y. Edwards, Y. Noh, A.D. Shah, and A.J. Whelton, 2021: Drinking water contamination from the thermal degradation of plastics: Implications for wildfire and structure fire response. *Environmental Science: Water Research & Technology*, **7** (2), 274–284. https://doi.org/10.1039/d0ew00836b

57. Gartner, J.E. and M. Jakob, 2019: Debris-flow risk assessment and mitigation design for pipelines in British Columbia, Canada. In: *7th International Conference on Debris-Flow Hazards Mitigation*. Golden, CO. Colorado School of Mines. https://doi.org/10.25676/11124/173156

58. Egan, D., C. Nelson, F. Roberts, A. Rose, A. Tucci, and R. Whytlaw, 2022: Complex economic consequence analysis to protect the maritime infrastructure. In: *2022 IEEE International Symposium on Technologies for Homeland Security (HST)*. 14–15 November 2022, 1–6. https://doi.org/10.1109/hst56032.2022.10024979

59. Ma, F., J.Y. Lee, D. Camenzind, and M. Wolcott, 2022: Probabilistic wildfire risk assessment methodology and evaluation of a supply chain network. *International Journal of Disaster Risk Reduction*, **82**, 103340. https://doi.org/10.1016/j.ijdrr.2022.103340

60. DOT, 2015: Vulnerability Assessment Scoring Tool User's Guide. U.S. Department of Transportation, Center for Climate Change and Environmental Forecasting, 34 pp. https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/scoring_tools_guide/vast_users_guide.pdf

61. National Academies of Sciences, Engineering, and Medicine, 2021: *Investing in Transportation Resilience: A Framework for Informed Choices*. The National Academies Press, Washington, DC, 156 pp. https://doi.org/10.17226/26292

62. FHWA, 2023: Resilience Pilots. U.S. Department of Transportation, Federal Highway Administration. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/

63. Houston-Galveston Area Council, 2021: Resilience and Durability to Extreme Weather in the H-GAC Region Pilot Program Report. Houston-Galveston Area Council. https://www.h-gac.com/getmedia/4a9d1f74-a43c-4279-8f82-f11da502e1e8/h-gac-resiliency-pilot-program-final-report.pdf

64. Hillsborough County Metropolitan Planning Organization, 2019: Resilient Tampa Bay: Transportation Pilot Program Project. U.S. Department of Transportation, Federal Highway Administration, Tampa, FL. https://planhillsborough.org/wp-content/uploads/2023/01/Final-TM-HillsboroughMPO-2045LRTP-ResilientTampaBay.pdf

65. An Act to Amend the Environmental Conservation Law, the Public Service Law, the Public Authorities Law, the Labor Law and the Community Risk and Resiliency Act, in Relation to Establishing the New York State Climate Leadership and Community Protection Act. S. 6599, A. 8429, State of New York, June 18, 2019. https://legislation.nysenate.gov/pdf/bills/2019/s6599

66. Resiliency Through Adaptation, Economic Vitality, and Equity Act of 2022. AB1384, Chapter 338, State of California, September 16, 2022. https://legiscan.com/CA/text/AB1384/id/2424711

67. Caltrans, 2020: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 2. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d2-adaptation-priorities-report-2020-a11y.pdf

68. Caltrans, 2020: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 3. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d3-adaptation-priorities-report-2020-a11y.pdf

69. Caltrans, 2020: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 4. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d4-adaptation-priorities-report-2020-v2-a11y.pdf

70. Caltrans, 2020: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 6. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d6-adaptation-priorities-report-2020-a11y.pdf

71. Caltrans, 2020: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 8. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d8-adaptation-priorities-report-2020-a11y.pdf

72. Caltrans, 2020: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 10. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d10-adaptation-priorities-report-2021-a11y.pdf

73. Caltrans, 2020: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 11. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d11-adaptation-priorities-report-2020-a11y.pdf

74. Caltrans, 2020: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 12. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d12-adaptation-priorities-report-2020-a11y.pdf

75. Caltrans, 2021: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 1. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d1-adaptation-priorities-report-2021-a11y.pdf

76. Caltrans, 2021: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 5. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d5-adaptation-priorities-report-2021-a11y.pdf

77. Caltrans, 2021: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 7. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d7-adaptation-priorities-report-2021-a11y.pdf

78. Caltrans, 2021: 2020 Adaptation Priorities Reports: Caltrans Adaptation Priorities Report—District 9. State of California, California Department of Transportation. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d9-adaptation-priorities-report-2021-a11y.pdf

79. FTA, 2023: Sustainable Transit for a Healthy Planet Challenge. U.S. Department of Transportation, Federal Transit Administration. https://www.transit.dot.gov/climate-challenge

80. Chester, M.V. and B. Allenby, 2021: Transportation for the Anthropocene. *Transfers Magazine*. https://transfersmagazine.org/magazine-article/issue-7/transportation-for-the-anthropocene/

81. Bui, A., P. Slowik, and N. Lutsey, 2021: Evaluating Electric Vehicle Market Growth Across U.S. Cities. International Council on Clean Transportation, 19 pp. https://theicct.org/publication/evaluating-electric-vehicle-market-growth-across-u-s-cities/

82. Howard, B., S. Vaidyanathan, C. Cohn, N. Henner, and B. Jennings, 2021: The State Transportation Electrification Scorecard. American Council for an Energy-Efficient Economy, Washington, DC. https://www.aceee.org/electric-vehicle-scorecard

83. *Joint Hearing on Transportation Cybersecurity: Protecting Planes, Trains, and Pipelines From Cyber Threats, House of Representatives, Subcommittee on Cybersecurity, Infrastructure Protection, and Innovation and the Subcommittee on Transportation and Maritime Security of the Committee on Homeland Security*, 2021: United States Congress, One Hundred Seventeenth, First Session. https://www.congress.gov/117/chrg/CHRG-117hhrg46812/CHRG-117hhrg46812.pdf

84. MTI, 2020: How Prepared Is Transit for a Cyber Attack? Mineta Transportation Institute, San Jose, CA. https://transweb.sjsu.edu/press/how-prepared-transit-cyber-attack

85. TSA, 2021: Surface Transportation Cybersecurity Toolkit. Transportation Security Administration. https://www.tsa.gov/for-industry/surface-transportation-cybersecurity-toolkit

86. Lempert, R.J., M. Miro, and D. Prosdocimi, 2021: A DMDU Guidebook for Transportation Planning Under a Changing Climate. Lefevre, B. and E. Monter, Eds. Inter-American Development Bank. https://doi.org/10.18235/0003042

87. ASCE, 2020: Policy Statement 500 - Resilient Infrastructure Initiatives. American Society Civil Engineers. https://www.asce.org/advocacy/policy-statements/ps500---resilient-infrastructure-initiatives

88. ASCE, 2021: Policy Statement 418 - The Role of the Civil Engineer in Sustainable Development. American Society of Civil Engineers. https://www.asce.org/advocacy/policy-statements/ps418---the-role-of-the-civil-engineer-in-sustainable-development

89. ASCE, 2021: Policy Statement 451 - Life-Cycle Cost Analysis. American Society Civil Engineers. https://www.asce.org/advocacy/policy-statements/ps451---life-cycle-cost-analysis

90. ASCE, 2021: Policy Statement 556 - Owners Commitment to Sustainability. American Society Civil Engineers. https://www.asce.org/advocacy/policy-statements/ps556---owners-commitment-to-sustainability

91. ASCE, 2023: ASCE NOAA Taskforce. American Society of Civil Engineers. https://www.asce.org/initiatives/asce-noaa-taskforce

92. Ayyub, B.M., Ed. 2018: *Climate-Resilient Infrastructure: Adaptive Design and Risk Management*. American Society of Civil Engineers, Reston, VA. https://doi.org/10.1061/9780784415191

93. California Building Standards Commission, 2019: 2019 California Green Building Standards Code, Title 24, Part 11. International Code Council, Washington, DC. https://calgreenenergyservices.com/wp/wp-content/uploads/2019_california_green_code.pdf

94. DOT, 2017: Bridges and Structures: Geohazards. U.S. Department of Transportation, Federal Highway Administration. https://www.fhwa.dot.gov/engineering/geotech/hazards/

95. ISI, 2018: Envision: Sustainable Infrastructure Framework Guidance Manual. Institute for Sustainable Infrastructure, Washington, DC. https://sustainableinfrastructure.org/wp-content/uploads/EnvisionV3.9.7.2018.pdf

96. TRB, 2019: Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure. National Academies of Sciences, Engineering, and Medicine, Transportation Research Board. https://apps.trb.org/cmsfeed/trbnetprojectdisplay.asp?projectid=4046

97. TRB, 2022: Design Guide and Standards for Infrastructure Resilience. National Academies of Sciences, Engineering, and Medicine, Transportation Research Board. https://apps.trb.org/cmsfeed/trbnetprojectdisplay.asp?projectid=4971

98. TRB, 2022: Pilot Test of Climate Change Design Practices Guide for Hydrology and Hydraulics. National Academies of Sciences, Engineering, and Medicine, Transportation Research Board. https://apps.trb.org/cmsfeed/trbnetprojectdisplay.asp?projectid=4858

99. Carluccio, S., J. Mian, L. Andrews, and O. Pritchard, 2021: A Review of the Landscape of Guidance, Tools and Standards for Sustainable and Resilient Infrastructure. International Coalition for Sustainable Infrastructure. https://www.resilienceshift.org/publication/a-review-of-the-landscape-of-guidance-tools-and-standards-for-sustainable-and-resilient-infrastructure/

100. GAO, 2021: Climate Resilience: Options to Enhance the Resilience of Federally Funded Roads and Reduce Fiscal Exposure. GAO-21-436. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-21-436.pdf

101. GIZ GmbH, 2022: Sustainable Infrastructure Tool Navigator. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. https://sustainable-infrastructure-tools.org/get-started/

102. TRB, 2020: Guide Specification for Service Life Design of Highway Bridges. National Academies of Sciences, Engineering, and Medicine, Transportation Research Board. https://trid.trb.org/view/1758793

103. USGBC-LA, 2016: Building Resilience Los Angeles: A Primer for Facilities. US Green Building Council-Los Angeles. https://usgbc-la.org/programs/climate-resilience/

104. Kumar, P., L. Morawska, C. Martani, G. Biskos, M. Neophytou, S. Di Sabatino, M. Bell, L. Norford, and R. Britter, 2015: The rise of low-cost sensing for managing air pollution in cities. *Environment International*, **75**, 199–205. https://doi.org/10.1016/j.envint.2014.11.019

105. Donadee, J., R. Shaw, O. Garnett, E. Cutter, and L. Min, 2019: Potential benefits of vehicle-to-grid technology in California: High value for capabilities beyond one-way managed charging. *IEEE Electrification Magazine*, **7** (2), 40–45. https://doi.org/10.1109/mele.2019.2908793

106. Feng, K., N. Lin, S. Xian, and M.V. Chester, 2020: Can we evacuate from hurricanes with electric vehicles? *Transportation Research Part D: Transport and Environment*, **86**, 102458. https://doi.org/10.1016/j.trd.2020.102458

107. Silverman, A.I., T. Brain, B. Branco, P.s.v. Challagonda, P. Choi, R. Fischman, K. Graziano, E. Hénaff, C. Mydlarz, P. Rothman, and R. Toledo-Crow, 2022: Making waves: Uses of real-time, hyperlocal flood sensor data for emergency management, resiliency planning, and flood impact mitigation. *Water Research*, **220**, 118648. https://doi.org/10.1016/j.watres.2022.118648

108. Subramanya, K. and S. Kermanshachi, 2021: Impact of COVID-19 on transportation industry: Comparative analysis of road, air, and rail transportation modes. In: *International Conference on Transportation and Development 2021*. Virtual Conference, 8–10 June 2021, 230–242. https://doi.org/10.1061/9780784483534.020

109. Dowds, J. and G. McRae, 2021: Workforce Development Needs of Transportation Sector Climate Adaptation Professionals. National Center for Sustainable Transportation, 48 pp. https://doi.org/10.7922/g2kk993x

110. GAO, 2022: FEMA Workforce: Long-Standing and New Challenges Could Affect Mission Success: Statement of Chris P. Currie, Director, Homeland Security and Justice. GAO-22-105631. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-22-105631.pdf

111. TRB, 2019: Transportation Workforce of the Future. Number 323. National Academies of Sciences, Engineering, and Medicine, Transportation Research Board. https://onlinepubs.trb.org/onlinepubs/trnews/trnews323.pdf

112. NIAC, 2021: Workforce and Talent Management Study. National Infrastructure Advisory Council, 96 pp. https://www.cisa.gov/resources-tools/resources/national-infrastructure-advisory-council-workforce-and-talent-management

113. Bain, Paul G., Taciano L. Milfont, Y. Kashima, M. Bilewicz, G. Doron, Ragna B. Garðarsdóttir, Valdiney V. Gouveia, Y. Guan, L.-O. Johansson, C. Pasquali, V. Corral-Verdugo, Juan I. Aragones, A. Utsugi, C. Demarque, S. Otto, J. Park, M. Soland, L. Steg, R. González, N. Lebedeva, Ole J. Madsen, C. Wagner, Charity S. Akotia, T. Kurz, José L. Saiz, P.W. Schultz, G. Einarsdóttir, and N.M. Saviolidis, 2016: Co-benefits of addressing climate change can motivate action around the world. *Nature Climate Change*, **6** (2), 154–157. https://doi.org/10.1038/nclimate2814

114. Nieuwenhuijsen, M.J. and H. Khreis, 2020: Ch. 1. Transport and health; an introduction. In: *Advances in Transportation and Health*. Nieuwenhuijsen, M.J. and H. Khreis, Eds. Elsevier, 3–32. https://doi.org/10.1016/b978-0-12-819136-1.00001-2

115. Mueller, N., D. Rojas-Rueda, T. Cole-Hunter, A. de Nazelle, E. Dons, R. Gerike, T. Götschi, L. Int Panis, S. Kahlmeier, and M. Nieuwenhuijsen, 2015: Health impact assessment of active transportation: A systematic review. *Preventive Medicine*, **76**, 103–114. https://doi.org/10.1016/j.ypmed.2015.04.010

116. California Natural Resources Agency, 2022: Building Climate Resilience. State of California, California Natural Resources Agency. https://resources.ca.gov/initiatives/building-climate-resilience

117. Karthick, S., S. Kermanshachi, B. Rouhanizadeh, and M. Namian, 2021: Short- and long-term health challenges of transportation workforce due to extreme weather conditions. In: *Tran-SET 2021*. American Society of Civil Engineers, 39–51. https://doi.org/10.1061/9780784483787.005

118. Martín, B., E. Ortega, R. Cuevas-Wizner, A. Ledda, and A. De Montis, 2021: Assessing road network resilience: An accessibility comparative analysis. *Transportation Research Part D: Transport and Environment*, **95**, 102851. https://doi.org/10.1016/j.trd.2021.102851

119. Reid, R.L., 2022: How to make infrastructure more resilient against climate change. *Civil Engineering Magazine*. https://www.asce.org/publications-and-news/civil-engineering-source/civil-engineering-magazine/issues/magazine-issue/article/2022/01/how-to-make-infrastructure-more-resilient-against-climate-change

120. Zhou, Y., J. Wang, and H. Yang, 2019: Resilience of transportation systems: Concepts and comprehensive review. *IEEE Transactions on Intelligent Transportation Systems*, **20** (12), 4262–4276. https://doi.org/10.1109/tits.2018.2883766

121. EPA, 2011: The Benefits and Costs of the Clean Air Act from 1990 to 2020: Summary Report. U.S. Environmental Protection Agency, Office of Air and Radiation, 34 pp. https://www.epa.gov/sites/default/files/2015-07/documents/summaryreport.pdf

122. Alotaibi, R., M. Bechle, J.D. Marshall, T. Ramani, J. Zietsman, M.J. Nieuwenhuijsen, and H. Khreis, 2019: Traffic related air pollution and the burden of childhood asthma in the contiguous United States in 2000 and 2010. *Environment International*, **127**, 858–867. https://doi.org/10.1016/j.envint.2019.03.041

123. Anenberg, S.C., J. Miller, D.K. Henze, R. Minjares, and P. Achakulwisut, 2019: The global burden of transportation tailpipe emissions on air pollution-related mortality in 2010 and 2015. *Environmental Research Letters*, **14** (9), 094012. https://doi.org/10.1088/1748-9326/ab35fc

124. Garcia, E., K.T. Berhane, T. Islam, R. McConnell, R. Urman, Z. Chen, and F.D. Gilliland, 2019: Association of changes in air quality with incident asthma in children in California, 1993–2014. JAMA, **321** (19), 1906–1915. https://doi.org/10.1001/jama.2019.5357

125. Garcia, E., J. Johnston, R. McConnell, L. Palinkas, and S.P. Eckel, 2023: California's early transition to electric vehicles: Observed health and air quality co-benefits. *Science of The Total Environment*, **867**, 161761. https://doi.org/10.1016/j.scitotenv.2023.161761

126. Health Effects Institute, 2022: Systematic Review and Meta-analysis of Selected Health Effects of Long-Term Exposure to Traffic-Related Air Pollution. Special Report 23. Health Effects Institute. https://www.healtheffects.org/publication/systematic-review-and-meta-analysis-selected-health-effects-long-term-exposure-traffic

127. Du, B., M.C. Tandoc, M.L. Mack, and J.A. Siegel, 2020: Indoor $CO_2$ concentrations and cognitive function: A critical review. *Indoor Air*, **30** (6), 1067–1082. https://doi.org/10.1111/ina.12706

128. Karnauskas, K.B., S.L. Miller, and A.C. Schapiro, 2020: Fossil fuel combustion is driving indoor $CO_2$ toward levels harmful to human cognition. *GeoHealth*, **4** (5), e2019GH000237. https://doi.org/10.1029/2019gh000237

129. Peters, D.R., J.L. Schnell, P.L. Kinney, V. Naik, and D.E. Horton, 2020: Public health and climate benefits and trade-offs of U.S. vehicle electrification. *GeoHealth*, **4** (10), e2020GH000275. https://doi.org/10.1029/2020gh000275

130. Goldberg, D.L., S.C. Anenberg, D. Griffin, C.A. McLinden, Z. Lu, and D.G. Streets, 2020: Disentangling the impact of the COVID-19 lockdowns on urban $NO_2$ from natural variability. *Geophysical Research Letters*, **47** (17), e2020GL089269. https://doi.org/10.1029/2020gl089269

131. Kerr, G.H., D.L. Goldberg, and S.C. Anenberg, 2021: COVID-19 pandemic reveals persistent disparities in nitrogen dioxide pollution. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (30), e2022409118. https://doi.org/10.1073/pnas.2022409118

132. Laughner, J.L., J.L. Neu, D. Schimel, P.O. Wennberg, K. Barsanti, K.W. Bowman, A. Chatterjee, B.E. Croes, H.L. Fitzmaurice, D.K. Henze, J. Kim, E.A. Kort, Z. Liu, K. Miyazaki, A.J. Turner, S. Anenberg, J. Avise, H. Cao, D. Crisp, J.d. Gouw, A. Eldering, J.C. Fyfe, D.L. Goldberg, K.R. Gurney, S. Hasheminassab, F. Hopkins, C.E. Ivey, D.B.A. Jones, J. Liu, N.S. Lovenduski, R.V. Martin, G.A. McKinley, L. Ott, B. Poulter, M. Ru, S.P. Sander, N. Swart, Y.L. Yung, and Z.-C. Zeng, 2021: Societal shifts due to COVID-19 reveal large-scale complexities and feedbacks between atmospheric chemistry and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (46), e2109481118. https://doi.org/10.1073/pnas.2109481118

133. Demetillo, M.A.G., C. Harkins, B.C. McDonald, P.S. Chodrow, K. Sun, and S.E. Pusede, 2021: Space-based observational constraints on $NO_2$ air pollution inequality from diesel traffic in major US cities. *Geophysical Research Letters*, **48** (17), e2021GL094333. https://doi.org/10.1029/2021gl094333

134. Grabow, M.L., S. Spak, J. Sledge, S. Ventura, and J.A. Patz, 2009: Health co-benefits from green transportation: The triple-win biking project. *Epidemiology*, **20** (6), S263. https://doi.org/10.1097/01.ede.0000362879.73665.06

135. Maizlish, N., J. Woodcock, S. Co, B. Ostro, A. Fanai, and D. Fairley, 2013: Health cobenefits and transportation-related reductions in greenhouse gas emissions in the San Francisco Bay Area. *American Journal of Public Health*, **103** (4), 703–709. https://doi.org/10.2105/ajph.2012.300939

136. Peng, B., S. Erdoğan, A.A. Nasri, and Z. Zou, 2021: Towards a health-conscious transportation planning: A framework for estimating health impacts of active transportation at local level. *Journal of Transport & Health*, **22**, 101231. https://doi.org/10.1016/j.jth.2021.101231

137. Leyland, L.-A., B. Spencer, N. Beale, T. Jones, and C.M. van Reekum, 2019: The effect of cycling on cognitive function and well-being in older adults. *PLoS ONE*, **14** (2), e0211779. https://doi.org/10.1371/journal.pone.0211779

138. Maizlish, N., C. Jiang, and A. Weiher, 2021: User's Guide and Technical Manual: USA R/Shiny Version. Integrated Transport and Health Impact Model. http://cal-ithim.org/ithim/ITHIM_manual.pdf

139. WHO, 2021: Health Economic Assessment Tool (HEAT) for Walking and for Cycling. Kahlmeier, S., T. Götschi, N. Cavill, A.C. Fernandez, C. Brand, D.R. Rueda, J. Woodcock, P. Kelly, C. Lieb, P. Oja, C. Foster, H. Rutter, and F. Racioppi, Eds. World Health Organization, 73 pp. https://www.who.int/publications/i/item/health-economic-assessment-tool-(heat)-for-walking-and-for-cycling

140. Innes, J.E. and D.E. Booher, 2004: Reframing public participation: Strategies for the 21st century. *Planning Theory & Practice*, **5** (4), 419–436. https://doi.org/10.1080/1464935042000293170

141. EPA, 2022: Learn About Environmental Justice. U.S. Environmental Protection Agency. https://www.epa.gov/environmentaljustice/learn-about-environmental-justice

142. McGregor, D., S. Whitaker, and M. Sritharan, 2020: Indigenous environmental justice and sustainability. *Current Opinion in Environmental Sustainability*, **43**, 35–40. https://doi.org/10.1016/j.cosust.2020.01.007

143. DOT, 2023: Justice40 Initiative. U.S. Department of Transportation, accessed May 18, 2023. https://www.transportation.gov/equity-justice40

144. FHWA, 2023: Promoting Resilient Operations for Transformative, Efficient, and Cost-Saving Transportation (PROTECT) Program. U.S. Department of Transportation, Federal Highway Administration. https://www.fhwa.dot.gov/environment/protect/

145. Agusdinata, D.B., W. Liu, H. Eakin, and H. Romero, 2018: Socio-environmental impacts of lithium mineral extraction: Towards a research agenda. *Environmental Research Letters*, **13** (12), 123001. https://doi.org/10.1088/1748-9326/aae9b1

146. Dall-Orsoletta, A., P. Ferreira, and G. Gilson Dranka, 2022: Low-carbon technologies and just energy transition: Prospects for electric vehicles. *Energy Conversion and Management: X*, **16**, 100271. https://doi.org/10.1016/j.ecmx.2022.100271

147. Gaines, L., K. Richa, and J. Spangenberger, 2018: Key issues for Li-ion battery recycling. *MRS Energy & Sustainability*, **5** (1), 12. https://doi.org/10.1557/mre.2018.13

148. Duncan, D. and J. Graham, 2013: Road user fees instead of fuel taxes: The quest for political acceptability. *Public Administration Review*, **73** (3), 415–426. https://doi.org/10.1111/puar.12045

149. Reckien, D., S. Lwasa, D. Satterthwaite, D. McEvoy, F. Creutzig, M. Montgomery, D. Schensul, D. Balk, I.A. Khan, B. Fernandez, D. Brown, J.C. Osorio, M. Tovar-Restrepo, A. de Sherbinin, W. Feringa, A. Sverdlik, E. Porio, A. Nair, S. McCormick, and E. Bautista, 2018: Ch. 6. Equity, environmental justice, and urban climate change. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Rosenzweig, C., P. Romero-Lankao, S. Mehrotra, S. Dhakal, S. Ali Ibrahim, and W.D. Solecki, Eds. Cambridge University Press, Cambridge, UK, 173–224. https://doi.org/10.1017/9781316563878.013

150. Walls, M. and J. Hanson, 1999: Distributional aspects of an environmental tax shift: The case of motor vehicle emissions taxes. *National Tax Journal*, **52** (1), 53–65. https://doi.org/10.1086/ntj41789375

151. GCC, 2016: Fort Lauderdale, Florida - Highway A1A Redesign Project. Georgetown University, Georgetown Climate Center. https://www.adaptationclearinghouse.org/resources/fort-lauderdale-florida-highway-a1a-redesign-project.html

152. GCC, 2020: Piedras Blancas Highway 1 Realignment - Caltrans/San Luis Obispo. Georgetown University, Georgetown Climate Center. https://www.adaptationclearinghouse.org/resources/piedras-blancas-highway-1-realignment-caltrans-san-luis-obispo.html

153. Kaack, L.H., P. Vaishnav, M.G. Morgan, I.L. Azevedo, and S. Rai, 2018: Decarbonizing intraregional freight systems with a focus on modal shift. *Environmental Research Letters*, **13** (8), 083001. https://doi.org/10.1088/1748-9326/aad56c

154. EPA, 2022: Ports Emissions Inventory Guidance: Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emissions. EPA-420-B-22-011. U.S. Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1014J1S.pdf

155. Khaslavskaya, A. and V. Roso, 2020: Dry ports: Research outcomes, trends, and future implications. *Maritime Economics & Logistics*, **22** (2), 265–292. https://doi.org/10.1057/s41278-020-00152-9

156. Giuliano, G., L. White, and S. Dexter, 2018: Developing Markets for Zero-Emission Vehicles in Goods Movement. National Center for Sustainable Transportation. https://rosap.ntl.bts.gov/view/dot/35513

157. Tetra Tech, Gladstein, and Neandross and Associates, 2020: Clean Air Action Plan: 2018 Feasibility Assessment for Drayage Trucks. Port of Long Beach and Port of Los Angeles. https://cleanairactionplan.org/download/222/other-documents/5029/final-drayage-truck-feasibility-assessment.pdf

Fifth National Climate Assessment: Chapter 14

# Air Quality

# Chapter 14. Air Quality

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# Introduction

Good air quality is vital to human health and the environment. Ozone and fine particulate matter ($PM_{2.5}$) are air pollutants with widespread health and environmental effects that derive from emissions from a variety of natural and human-caused sources, including industry, power plants, vehicles, and agriculture. Ozone is a colorless gas that forms in the atmosphere from emissions of other compounds. At ground level, ozone is a powerful oxidant that, when inhaled, affects the respiratory and cardiovascular system, causing a wide range of health outcomes including lung damage and premature mortality.[1,2] It also damages crops and natural vegetation.[1,3] $PM_{2.5}$ is defined as airborne particles with a diameter of 2.5 micrometers and smaller—about 30 times smaller than the width of a human hair. These small particles can be inhaled into the lungs, leading to health problems including cardiovascular disease, adverse birth outcomes, neurological disease, and increased risk of death.[4,5,6,7,8,9,10] $PM_{2.5}$ is a complex mixture of solid and liquid substances,[11] including particles emitted directly from combustion and those formed in the atmosphere from gases emitted from natural and human sources. $PM_{2.5}$ also contributes to regional haze, which can impair enjoyment of scenic vistas, including in national parks.

Ground-level ozone and $PM_{2.5}$ have declined in the US due to programs that lowered emissions. From 2000 to 2020, extreme ozone levels (98th percentile) declined by 18%,[12] and annual average $PM_{2.5}$ concentrations declined by 41%.[13] Continued reductions in human-caused emissions are projected to bring still cleaner air in the US.[14,15]

Despite these improvements, in 2021 nearly 102 million people lived in areas where pollution levels exceeded health-based air quality standards.[13] Estimates of annual US deaths from exposure to ambient ozone and $PM_{2.5}$ range from about 60,000[16]—more deaths than from either motor vehicle accidents, kidney disease, breast cancer, or prostate cancer—to 260,000[17,18,19] or more,[20] valued at $750 billion to $3 trillion (in 2022 dollars).[21,22] Air pollution damages to US crops are estimated at approximately $12 billion annually (in 2022 dollars).[23] The negative impacts of air pollution are not distributed equally, with communities of color and low-income communities disproportionately burdened.[24,25]

Climate change, driven mainly by human greenhouse gas (GHG) emissions that are not harmful to breathe at typical atmospheric levels, affects air pollutant concentrations through multiple pathways (KM 14.1) including wildfire smoke (KM 14.2) and affects aeroallergens (KM 14.4), with effects on health. Air pollutants also affect climate (KM 3.1), and the main sources of air pollutants are also the main sources of GHG emissions, suggesting that there is opportunity to address climate and air quality goals simultaneously (KM 14.5). Current inequities in air pollution exposure may be alleviated or worsened by the impacts of climate change and actions to reduce GHG emissions (KM 14.3).

## Key Message 14.1

## Climate Change Will Hamper Efforts to Improve US Air Quality

Climate change is projected to worsen air quality in many US regions (*medium confidence*), thereby harming human health and increasing premature death (*very likely*, *high confidence*). Extreme heat events, which can lead to high concentrations of air pollution, are projected to increase in severity and frequency (*very likely*, *very high confidence*), and the risk of exposure to airborne dust and wildfire smoke will increase with warmer and drier conditions in some regions (*very likely*, *high confidence*). Reducing air pollution concentrations will unequivocally help protect human health in a changing climate.

Air pollution concentrations are determined by natural and human-caused emissions and by atmospheric conditions, including temperature, humidity, and winds. Climate change is projected to worsen air quality in many regions, harming human health. Some of the largest increases in $PM_{2.5}$ and ozone exposure are expected in heat- and drought-prone regions (Figure 14.1) and in areas where vulnerable populations live (KM 14.3). For example, increasing heat and drought already contribute to more frequent wildfires and associated smoke episodes (KMs 14.2, 7.1). Severe climate change, with a US average warming of 9°–14°F, would increase annual US air pollution–related deaths by about 25,000 in 2100, relative to 2000.[26,27] This estimate assumes population growth but no change in emissions, including wildfire smoke. Given that wildfires and smoke $PM_{2.5}$ are projected to increase in a warmer climate (KM 14.2), this mortality rate may be an underestimate.

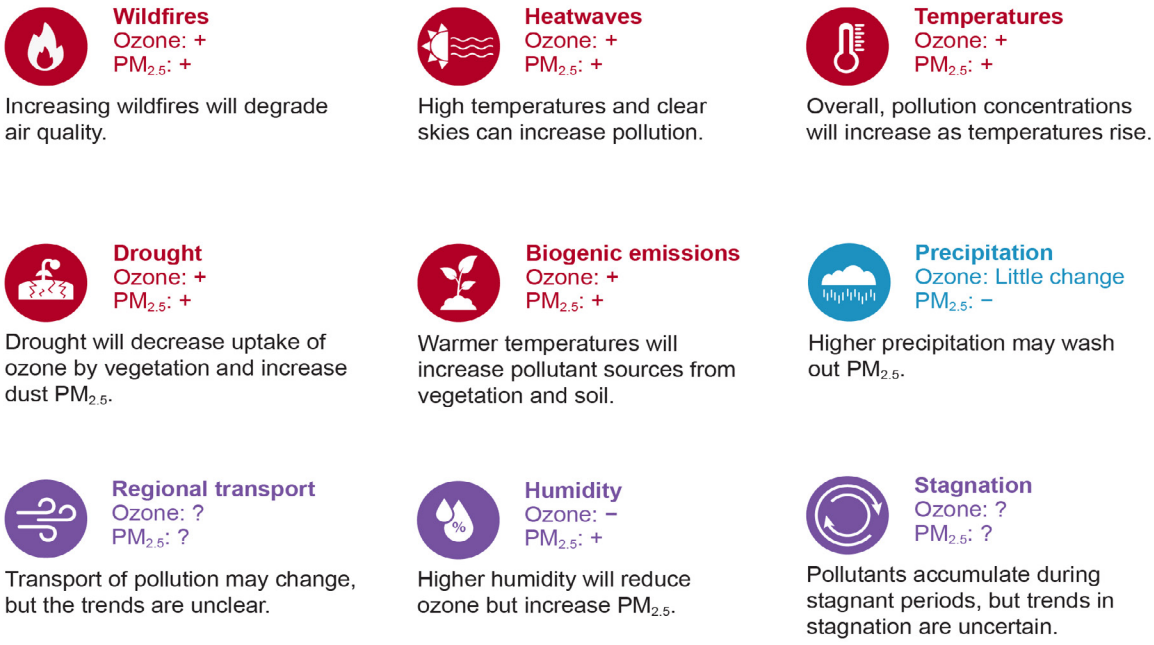
Climate change is expected to alter meteorology over the US in several ways that will directly degrade air quality (Figure 14.1). For example, ozone levels are higher on warm, sunny days because the chemical reactions that produce ozone speed up with temperature and sunlight. Exposure to these short-term ozone episodes has been linked to increased mortality.[28] Some gases that produce ozone and $PM_{2.5}$ come from soils and vegetation, and these emissions are sensitive to temperature and rainfall. Such processes typically lead to higher pollution levels during heatwaves, when exposure to $PM_{2.5}$ appears to be especially harmful.[29,30,31,32]

Local air pollution events are also strongly tied to large-scale weather patterns.[33,34,35,36] For example, cold fronts sweep clean air across the eastern US, clearing the air of pollution.[37] How climate change will affect these large-scale patterns is not well known. In the eastern US, the largest and most persistent pollution events often co-occur with extreme heat.[38] Air stagnation events, when weak winds provide little ventilation near the ground, promote pollution accumulation. Co-occurrences of heat and air stagnation are projected to increase with climate change.[39] Air pollution is also expected to worsen as the warm season lengthens, with greater pollution during the spring and autumn.[40,41] Other meteorological changes accompanying climate change may improve air quality. For example, increasing humidity may reduce ozone through chemical reactions, while increasing precipitation may remove $PM_{2.5}$ from the atmosphere (Figure 14.1).

Methane, a key GHG that contributes to near-term warming (KM 14.5), is a source of global background ozone when it undergoes chemical oxidation in the presence of nitrogen oxides.[42,43] Continued growth in methane emissions from wetlands and human activities would raise background ozone levels, including in winter (KM 3.1),[44,45] increasing the potential for a longer ozone season that begins earlier in the spring.[46] As with ozone episodes, long-term exposure to background ozone also increases mortality.[2,47]

The response of ozone and $PM_{2.5}$ to climate change—and their associated impacts on health—will vary regionally, reflecting the net balance of several complex chemical, meteorological, and small-scale processes, which vary spatially and over time (Figure 14.1).[48,49,50] Across the Midwest and Northeast, year-round ozone is expected to increase by 2035 under a very high scenario (RCP8.5).[51] In California and the Northeast, increasing temperatures under a moderate scenario (RCP4.5) would double the number of severe ozone episodes by the 2050s relative to the early 2000s,[52] with further increases in summer average ozone in these regions by 2100.[53] Projecting future $PM_{2.5}$ is complicated, as different types of $PM_{2.5}$ are expected to respond differently to changing climate.[51,54] Wildfires are expected to increase smoke $PM_{2.5}$ in the West and Alaska (KM 14.2). The rugged western topography makes it particularly susceptible to $PM_{2.5}$ increases, especially in winter when mountain valleys trap polluted air.[55] Declines in lake area in some areas of the mountainous West, driven mainly by human water use but also by changing climate, have exposed lakebeds and increased dust emissions.[56,57,58] These declines in lake area are projected to continue as temperatures rise and snowpack diminishes (KM 4.1), with further increases in dust.[59,60,61] In the arid Southwest, dust concentrations are expected to double by 2100, compared to 2010, due to warmer and drier conditions (KMs 6.1, 28.3, 28.4).[62,63] Multiple studies agree that climate change is expected to increase $PM_{2.5}$ concentrations in the Northeast.[40,49,64]

## Climate Change Impacts on Ozone and Fine Particulate Matter ($PM_{2.5}$) over the United States

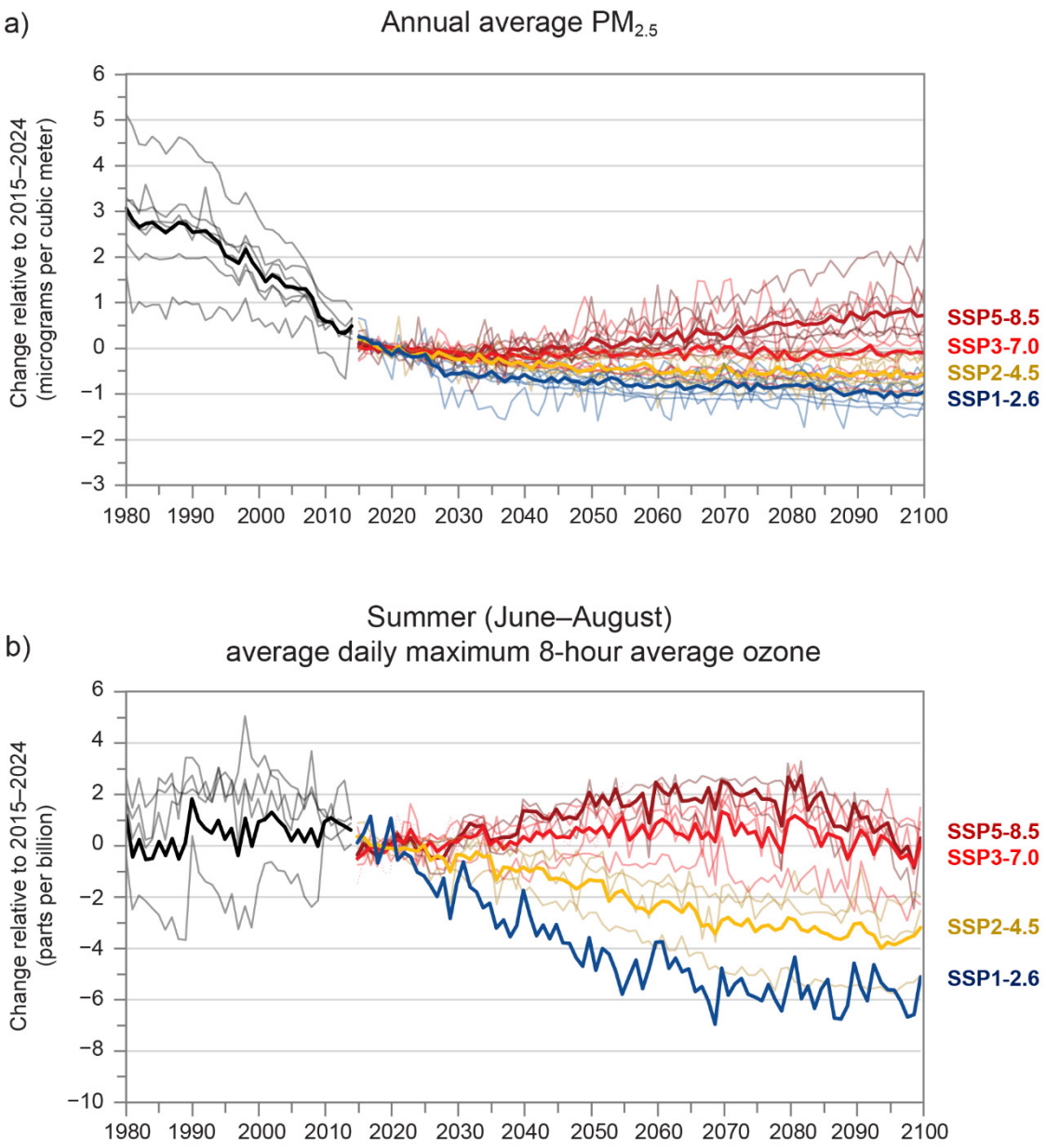



**Climate change will have varying effects on ozone and fine particulate matter ($PM_{2.5}$) concentrations, including through impacts on weather-sensitive emissions.**

**Figure 14.1.** Climate change is projected to alter concentrations of two key US air pollutants, ozone and $PM_{2.5}$, through several processes. Red icons signify increased ozone and $PM_{2.5}$, and the blue icon denotes decreased $PM_{2.5}$. Plus and minus signs indicate the expected pollutant response to climate-driven changes in meteorology. Question marks and purple icons denote uncertainty in either the response or in how the meteorological process will change with climate change. Given uncertainties and regional differences in pollution responses, the magnitude of these responses is not presented. Key Messages 14.1 and 14.2 provide more detailed descriptions of the mechanisms involved. Adapted from The Royal Society 2021[65] [CC BY 4.0].

The adverse effect of climate change on the air we breathe is known as the climate penalty on air quality, in which climate change counteracts some of the benefits expected from emissions reductions.[66] Figure 14.2 illustrates how air quality can vary under different scenarios of air pollution sources and GHGs in future decades. In general, climate change is expected to worsen air quality, although the actions that policymakers and communities take today could counteract this outcome. Steeper reductions in the human-caused emissions that contribute to ozone and $PM_{2.5}$ are expected to lessen this climate penalty and limit adverse health effects.[15,64,67,68]

## Simulated Historical and Projected Changes in Fine Particulate Matter ($PM_{2.5}$) and Ozone




**Reductions in human-caused emissions that contribute to ozone and fine particulate matter ($PM_{2.5}$) are expected to improve air quality in a changing climate.**

**Figure 14.2.** Future air quality depends on both air pollution control measures and climate change. Modeled pollutant concentrations are shown averaged over the contiguous US, with the historical period in black and projections in various colors, for (**a**) annual average $PM_{2.5}$ and (**b**) summer (June–August) average daily maximum 8-hour average ozone, a metric of ozone pollution. Trends are shown relative to the 2015–2024 average value. Historical air quality improvements reflect clean air policies. Thick lines are multimodel average values. Thin lines show individual model simulations, indicating uncertainties from modeled processes and natural weather variability for each scenario. The focus on the contiguous states reflects the stronger influence from domestic emissions compared to other US regions (Alaska, Hawai'i and the US-Affiliated Pacific Islands, and the US Caribbean), where the balance of processes contributing to pollution and responses to climate change are expected to differ. These projections do not include the expected strong influence of climate change on wildfire smoke. Model simulations are described by Turnock et al. 2020.[15] Figure credit: Massachusetts Institute of Technology. See figure metadata for additional contributors.

## Key Message 14.2

### Increasing Wildfire Smoke Is Harming Human Health and Catalyzing New Protection Strategies

Wildfires emit gases and fine particles that are harmful to human health, contributing to premature mortality, asthma, and other health problems (*very high confidence*). Climate change is contributing to increases in the frequency and severity of wildfires, thereby worsening air quality in many regions of the contiguous US and Alaska (*likely*, *high confidence*). Although large challenges remain, new communication and mitigation measures are reducing a portion of the dangers of wildfire smoke (*medium confidence*).

Large wildfires have become more frequent in the western US in recent decades. While wildfires occur naturally, climate change and other human influences have increased their likelihood (Focus on Western Wildfires; KM 28.5; Figure A4.14).[69] Wildfires are projected to increase in many regions over the coming century (KM 27.2).[70,71,72,73] Smoke pollutants emitted by wildfires negatively impact human health, visibility, and solar energy generation.[74,75] Wildland fires are the largest contributors to $PM_{2.5}$ concentrations in some parts of the western US[74,76,77] and impact air quality across the US (Figure 14.3). These concentrations could increase, particularly in the western US, by the end of the century,[78] offsetting improvements from reduced human-caused air pollutant emissions.[71,79]

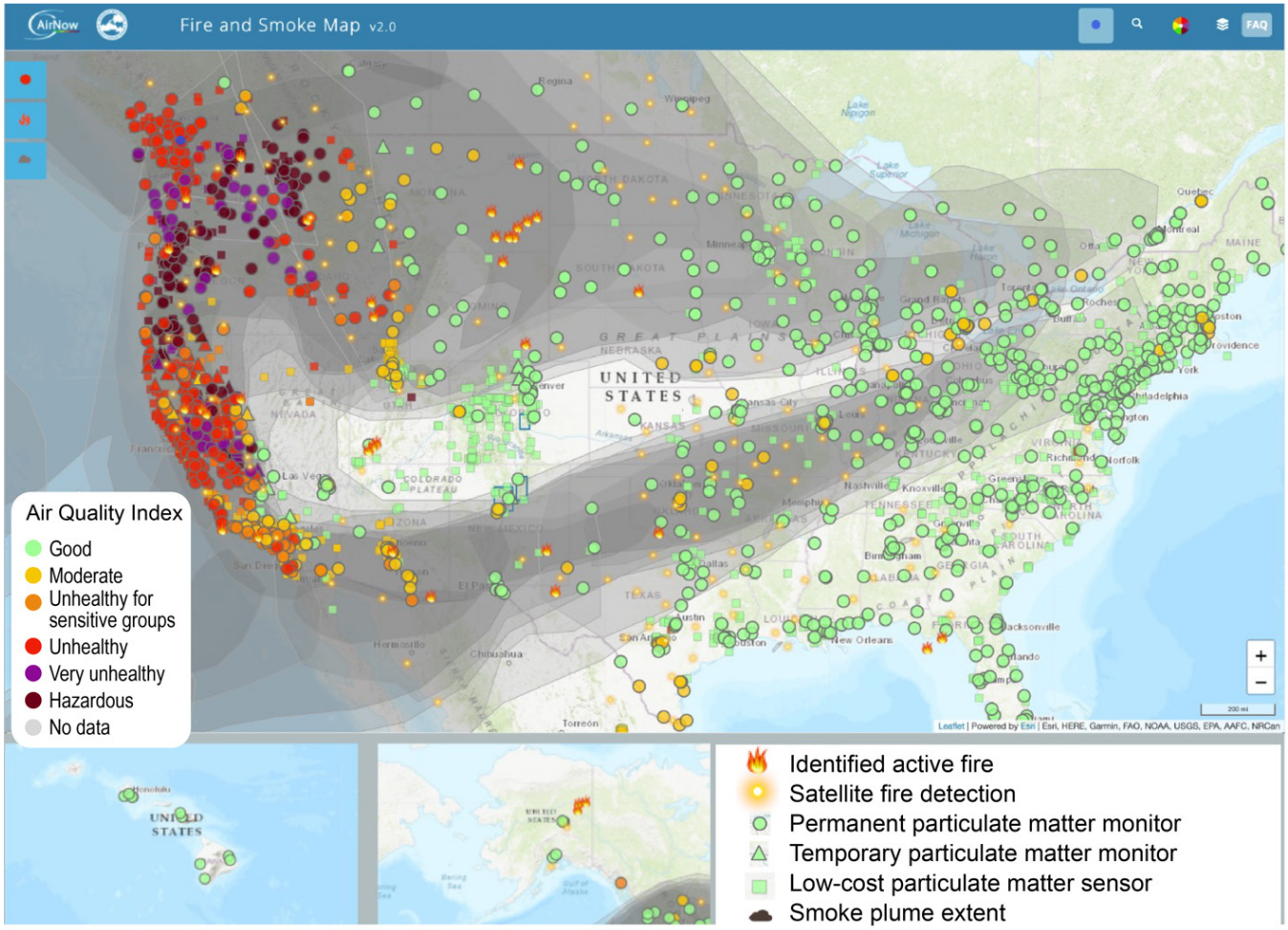
Wildfires emit $PM_{2.5}$ and other air pollutants, including volatile organic compounds (VOCs), nitrogen oxides (which contribute to ozone generation in plumes), and toxic gaseous and particulate species.[74,77] Since publication of the Fourth National Climate Assessment in 2018, studies have revealed factors influencing the smoke pollutant mixture, including the following: 1) smoke enhancements to ozone may be amplified when smoke mixes with urban pollution;[80,81] 2) chemical reactions in plumes change the composition of smoke $PM_{2.5}$ but generally not its amount;[82] and 3) hazardous VOC concentrations generally decrease with plume age due to chemical losses,[77] but structures burning in wildfires could emit additional toxic material, increasing health risks in the wildland–urban interface.[74,83,84] Finally, microbes emitted by fires and transported in smoke suggest that the region biologically affected by fires is more extensive than previously thought.[85,86,87]

Human exposure to smoke pollutants is associated with mortality, asthma, and other respiratory problems, as well as worse outcomes for birth, COVID-19 infection rates (Focus on COVID-19 and Climate Change), and emotional well-being.[88,89,90,91,92,93,94,95] Smoke exposure in the US presently contributes to 1,000–9,000 hospital and emergency department visits and 6,000–30,000 deaths annually.[96,97] Smoke can disproportionately impact certain racial, ethnic, occupational, and age-related subpopulations in both urban and rural areas (KM 22.2),[76,98,99,100] but the most impacted subpopulations are not consistent across studies. As future wildfire activity increases in some US regions, mortality rates and respiratory hospitalizations attributable to wildfires are also expected to increase (KM 27.5).[71,101]

Fire is a natural part of many ecosystems. Land managers use prescribed fire to promote ecosystem health and to reduce the vulnerability to severe fires (KMs 7.3, 28.5),[102] especially in a changing climate.[103,104] Indigenous communities have long used fire to steward their environments (KM 16.3).[105,106] Prescribed fire emissions vary greatly by region and season[107] but are typically much lower per acre than those from wildfires.[74] Prescribed fire activity could increase in some regions as land managers attempt to reduce the frequency, intensity, and spread of wildfires in a changing climate (KM 7.3).[103,104] Although air quality and health impacts are associated with prescribed fire smoke (KM 22.2),[108] well-designed prescribed fires targeted for specific locations have the potential to reduce overall smoke exposure[109] and health impacts of subsequent wildfires.[110,111]

Advances in remote sensing and improved smoke prediction systems,[112,113,114,115,116] combined with better communications strategies,[117] are helping protect the public from unhealthy smoke conditions (Figure 14.3). Smoke exposure reduction techniques, including masks and portable air filters, can help people limit the amount of $PM_{2.5}$ that is inhaled during a smoke event,[117,118,119,120,121] as well as pollen and other particulate air pollution. Smoke forecasters synthesize modeled, satellite, and monitoring data to create daily forecasts[122] that reach the general public, including underserved communities—for example, through Spanish translations. Communication of these forecasts and techniques to reduce smoke exposure occurs through interagency federal,[117,123] state, and Tribal programs, as well as social media. However, people tend to take protective actions, such as staying indoors and using air filters, in response to symptoms from exposure rather than take preventive measures.[124] More work would be needed to quantify and communicate the benefits of exposure-reduction actions.[125,126]

## Impacts of Wildfire Smoke on Air Quality




**Wildfire smoke affects air quality across the country.**

**Figure 14.3.** Wildfire smoke can affect the daily lives of people across the country, as communicated in real time to the public on September 13, 2020, on the AirNow Fire and Smoke Map (https://fire.airnow.gov/). Monitors measuring particulate matter are color-coded by air quality index from green for good air quality to brown for hazardous. Here, unhealthy to hazardous air quality conditions are shown at multiple monitors (circle, triangle, and square icons) across the western US, and satellite imagery (gray) shows smoke extending across much of North America. On this day, the US Caribbean was free of smoke, and monitor or sensor data were not yet available, so the region is not shown. Data are not available for US-affiliated Pacific Islands. Adapted from EPA 2022.[127] Base map: Copyright © 2022 Esri and its licensors. All rights reserved.

## Key Message 14.3

### Air Pollution Is Often Worse in Communities of Color and Low-Income Communities

Communities of color, people with low socioeconomic status, and other marginalized populations are disproportionately harmed by poor air quality (*very high confidence*). In the coming decades, these same communities will, on average, face worsened cumulative air pollution burdens from climate change–driven hazards (*very likely*, *high confidence*). Decision-making focused on the fair distribution of air quality improvements, rather than on overall emissions reductions alone, is critical for reducing air pollution inequities (*high confidence*).

Air pollution disproportionately affects people of color and people with low socioeconomic status in both cities and rural places.[128,129,130,131] While air quality has improved over recent decades, air pollution disparities have persisted.[132,133,134,135,136,137] There is a clear pattern of more air pollution sources being located in communities of color and low-income neighborhoods. Diesel traffic exhaust is among the largest sources of air pollution inequalities in urban areas,[138] while other emitters, including industrial facilities,[25,139] prescribed agricultural burns,[140] concentrated animal feeding operations,[141,142,143,144,145] power generation,[146] and oil and gas infrastructure,[147,148] contribute to air pollution disparities in cities and rural environments. Racism in historical practices and policies has contributed to ongoing inequities, protecting White areas from pollution and disinvesting in and off-loading those costs onto communities of color, for example, through redlining and housing segregation.[149,150,151]

The health impacts of the unequal distribution of air pollution are magnified by factors including reduced access to nutrition, social and institutional support, and healthcare, as well as psychosocial stress from racism and poverty.[152] As a result, a given level of air pollution can cause more harm to people of color and those with lower socioeconomic status.[30,152,153,154] Environmental inequalities often overlap, such as exposure to both poor air quality and higher-than-average urban heat (KM 21.3).[155,156] Exposure to air pollution and high air temperatures in combination can worsen health outcomes.[29,30,157,158] Environmental inequalities also often compound in ways that exacerbate negative impacts; for example, reduced tree cover, common in urban communities of color,[159] intensifies urban heat (KM 12.2) and affects air quality (KM 14.1). Disparities in air-conditioning access[160,161] and other housing differences may increase infiltration of outdoor air pollution and wildfire smoke into homes and schools in communities of color and lower-income neighborhoods,[162] and low-income households may have less ability to adopt in-home air filtration.

A 3.6°F (2°C) increase in average global temperatures relative to the 1986–2005 average is projected to worsen $PM_{2.5}$-related premature mortality for African Americans over age 65 by 40%–60% more than for people of other racial and ethnic groups.[155] This same temperature change is projected to cause substantially higher rates of $PM_{2.5}$-related asthma for African American children and smaller, but still disproportionate, increased rates for Latino, Asian, Pacific Islander, and American Indian and Alaska Native children. In New York City and Newark, New Jersey, projected trends in air stagnation are expected to worsen inequalities in concentrations of nitrogen dioxide ($NO_2$),[163] an air pollutant associated with asthma.[164,165] The impact of climate change on air quality–related inequalities may differ depending on the sources of pollution and whether pollutants are emitted directly or formed through chemistry (KM 14.1). However, climate change can increase cumulative and unequal air quality–related health burdens, such as from the combined effects of air pollution and temperature, even if air pollution itself does not worsen.[29,30,157,158]

Actions to address climate change through GHG regulation will also affect air quality, with the distribution of benefits dependent on the mitigation approach. Programs focusing on GHG sources with the lowest mitigation costs have had mixed impacts on air pollution equity.[166,167] In California, GHG regulation through carbon cap-and-trade increased emissions of combustion-related air pollutants in communities of color

and low-income neighborhoods.[168] Approaches focused on lowering aggregate emissions across a large geographic region, or from a single emissions category, have been shown to be less effective than interventions aimed at reducing air pollution inequalities for a specific location.[169] Solutions can be designed to reduce disparities and overcome the challenges associated with GHG regulation.[170,171]

## Box 14.1. Environmental Justice, Air Pollution, and Climate Change: Houston, Texas

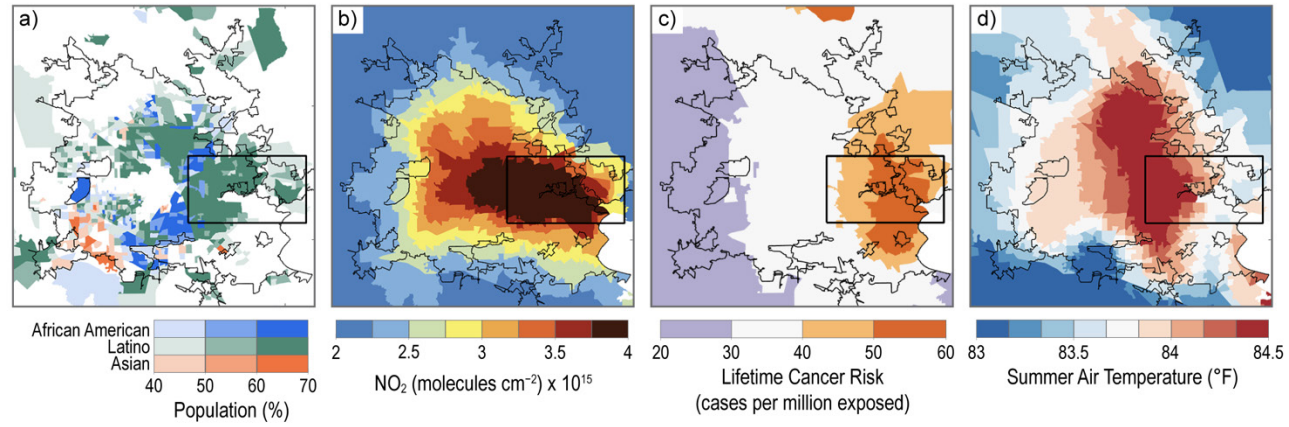
Houston's Ship Channel region is a patchwork of chemical refineries, freeways, homes, and playgrounds (Figure 14.4; Box 26.1). Air pollution levels along this busy industrial waterway, connecting downtown Houston to Galveston Bay, are among the highest in the city (Figure 14.5). Flares and odors are commonplace,[172,173,174] and community concerns about health impacts are often ignored. Many of Houston's African American, Latino, and working-class families live in the neighborhoods of the Ship Channel, where they are more likely to breathe harmful cancer-causing air pollution from diesel trucks and refineries.[138,175,176,177,178,179,180] Communities living at the fenceline of the petrochemical industry face ongoing vulnerabilities, such as dual exposure to air pollution and heat and endangerment from damages to petrochemical facilities caused by stronger hurricanes (KMs 9.2, 15.2). In 2017, Hurricane Harvey triggered widespread industrial releases of hazardous air pollutants throughout the Houston Ship Channel.[181,182,183] Houston is also the stage for foundational scholarship on environmental justice by Dr. Robert Bullard (KM 20.3), where community organizations lead work to reduce air pollution and make communities more resilient to climate change.

### Air Pollution Exposure at Home in the Houston Ship Channel Region

**Industries expose people living near the Ship Channel—often African American, Latino, and low-income residents—to harmful air pollution.**

**Figure 14.4.** Nighttime industrial flaring exposes residents to air pollution near the Houston Ship Channel in the Deepwater community in Pasadena, Texas, a primarily African American, Latino, and low-income neighborhood. Photo credit: ©Cassandra Casados-Klein, Air Alliance Houston.

## Air Pollution and Temperature Inequalities in Houston, Texas




**Air pollution, its health impacts, and temperatures are unequally distributed across Houston, Texas.**

**Figure 14.5.** Air quality and temperatures vary across Houston, Texas (urbanized area outlined in black). (**a**) For each neighborhood, the largest racial or ethnic group is shown: African American (blue), Latino (green), and Asian (orange). Higher-than-average levels of (**b**) nitrogen dioxide ($NO_2$; in 2019), (**c**) lifetime cancer risks associated with chronic air pollution exposure per million equally exposed people (2018), and (**d**) summer (June–August) air temperatures (2020) are found in neighborhoods that are primarily African American and Latino, especially those surrounding the Ship Channel (black box). There is variability in time and at very fine spatial scales that may not be captured here. Figure credit: University of Virginia, Columbia University, and Montana State University.

## Key Message 14.4

## Climate Change Is Worsening Pollen Exposures and Adversely Impacting Health

Increased allergen exposure damages the health of people who suffer from allergies, asthma, and chronic obstructive pulmonary disease (COPD) (*very high confidence*). Human-caused climate change has already caused some regions to experience longer pollen seasons and higher pollen concentrations (*very likely*, *high confidence*), and these trends are expected to continue as climate changes (*very likely*, *high confidence*). Increasing access to allergists, improved diagnosis and disease management, and allergy early warning systems may counteract the health impacts of increasing pollen exposure (*high confidence*).

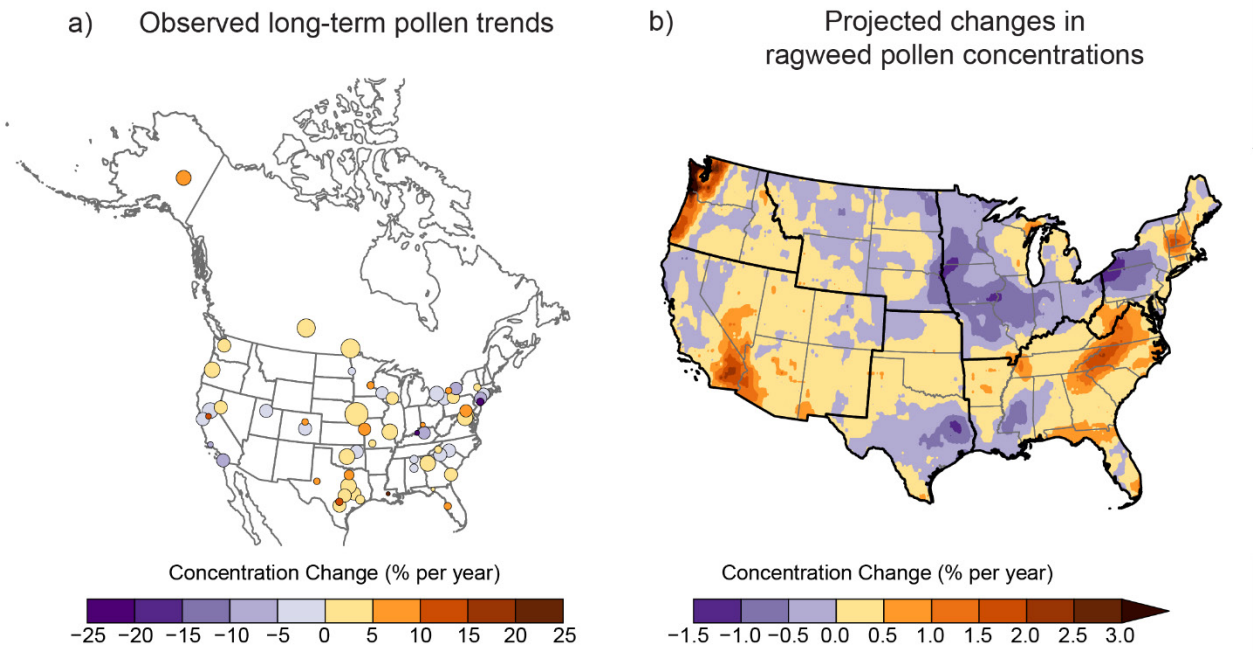
Allergic airway disease, including allergic rhinitis and asthma, is widespread in the US, is becoming more prevalent, and imposes a burden of several billion dollars in healthcare costs and lost productivity annually.[184] Exposure to allergenic pollens and molds (aeroallergens) triggers allergic disease development.[185,186,187] Co-exposure to aeroallergens and pollutants like ozone, nitrogen oxides, and $PM_{2.5}$ can exacerbate allergic airway disease symptoms.[188,189,190] Aeroallergen exposure can compromise the body's antiviral defenses, possibly increasing susceptibility to respiratory viral infections in both allergic and nonallergic people.[186,191] It is also probable that pollen exposure is associated with COPD mortality.[192] Pollen can also transport viruses.[193]

Local climate affects emissions of allergenic tree and grass pollens and fungal spores. Climate change is altering pollen season characteristics for allergen-producing trees during spring and for grasses and weeds during summer and fall.[194] Rising atmospheric carbon dioxide ($CO_2$) can increase pollen allergenicity.[195,196,197]

Multiple US regions have experienced longer, more intense pollen seasons, with earlier start dates and increased emissions and airborne loads over the past 30 years, increasing the potential for exposures (Figure 14.6; KM 22.2).[187,194,196,198,199,200,201] For example, the season for ragweed pollen, a significant allergen, has lengthened since the 1990s (Figure A4.13), and its range has expanded northward;[202] ragweed grows faster, flowers earlier, and produces more pollen in high-$CO_2$ areas.[196,203] With climate change, ragweed pollen is projected to increase in most regions (Figure 14.6) and to co-occur with high ozone more frequently.[204,205] Likewise, the number of days with total pollen concentrations exceeding thresholds for triggering allergies is projected to increase in most US regions.[204,206,207,208]

Increasing frequency and intensity of heatwaves, storms, and floods associated with climate change can also intensify aeroallergen exposures. Mold proliferation is increased by floods. Thunderstorms can exacerbate respiratory allergy and asthma in patients with hay fever, and similar phenomena have been observed for molds.[209]

## Observed and Projected Pollen Changes Under Climate Change




**Pollen has been increasing in many US regions and is projected to continue to increase as climate changes.**

**Figure 14.6.** (**a**) Observed long-term pollen increases are shown as the linear trend of total annual pollen at 60 stations (1990–2018). (**b**) Modeled projected changes in average airborne ragweed pollen concentrations in 2047, relative to 2004, are shown for climate change conditions under a very high scenario (RCP8.5). Yellow and red shades indicate increases in pollen concentrations, and circle size in panel (a) reflects the number of years of data at each station. Observations are not available for many US states and affiliated territories, and the modeled projection does not include non-contiguous US states and territories. There is a net increase in concentration overall, with marked increases in certain areas and declines in others. (a) Adapted from Anderegg et al. 2021[194] [CC BY 4.0]; (b) adapted from Ren et al. 2022[210] [CC BY 4.0].

Allergic airway disease is underdiagnosed, and many therapies are underutilized.[211] Increasing access to allergists and diagnostic tests can help clarify what exposures drive allergies for individuals and aid in developing therapeutic plans including medical and immune therapies.[212] Staying indoors and wearing masks to reduce exposure, as well as avoidance of allergens through early warning systems[213] and other public health campaigns, can also reduce impacts.[214] Understanding of climatic influences on pollen exposures can inform diagnosis and disease management, but it remains unclear whether these and other advances can blunt the health impact of increased aeroallergen exposures as the climate warms.

## Key Message 14.5

### Policies Can Reduce Greenhouse Gas Emissions and Improve Air Quality Simultaneously

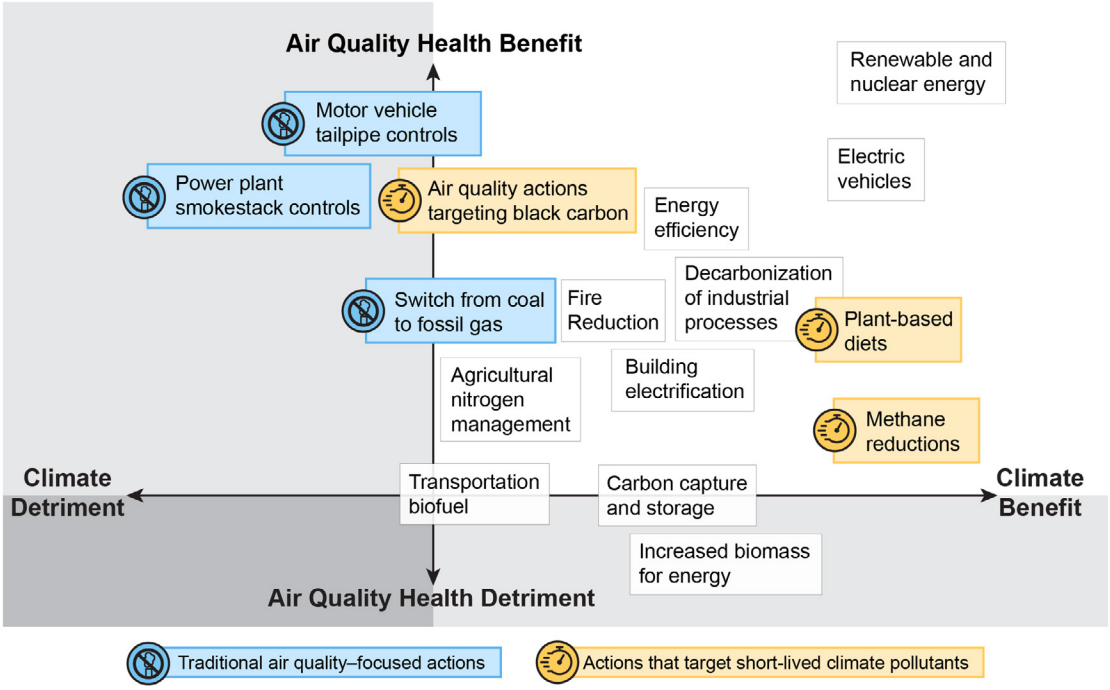
Substantial reductions in economy-wide greenhouse gas emissions would result in improved air quality and significant public health benefits (*very likely*, *high confidence*). For many actions, these benefits exceed the cost of greenhouse gas emission controls (*likely*, *high confidence*). Through coordinated actions emphasizing reduced fossil fuel use, improved energy efficiency, and reductions in short-lived climate pollutants, the US has an opportunity to greatly improve air quality while substantially reducing its climate impact, approaching net-zero $CO_2$ emissions (*high confidence*).

Fossil fuel energy use is responsible for 92.1% of US $CO_2$ emissions[215] and the majority of $PM_{2.5}$-induced deaths.[20,216] Consequently, actions to control GHGs, including reductions in energy demand or shifts toward cleaner energy sources, typically reduce air pollutant emissions from the same sources, benefiting air quality and health.

By contrast, actions that have substantially improved US air quality since 1990 generally did not reduce GHG emissions, as they focused on technologies that remove air pollutant emissions from power plants, industrial facilities, and vehicles but do not reduce fossil fuel consumption—and some actions increased fossil fuel use and GHG emissions (Figure 14.7).[215,217,218] In the past decade, fuel switching from coal toward renewables (wind and solar) and lower-emitting sources (fossil gas) has reduced emissions of both GHGs and air pollutants.[219,220]

To further improve air quality, more stringent smokestack and tailpipe controls on fossil fuel sources may be chosen. Alternatively, GHG mitigation scenarios that meet the long-term temperature goal of the Paris Agreement and approach net-zero emissions this century replace fossil fuels with cleaner energy sources and reduce overall energy use (Figure 14.7; KM 32.2).[221,222,223] This clean energy transition would provide air quality[224] and health benefits[225] beyond what smokestack and tailpipe controls can provide.

## Potential for Emissions-Reduction Actions to Achieve Air Quality and Climate Benefits

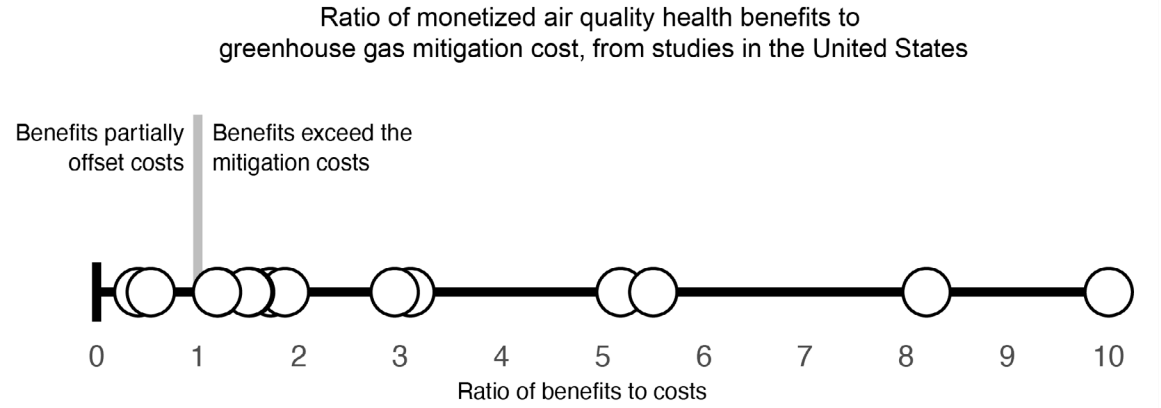



**Many emissions-reduction actions can achieve multiple benefits for climate, air quality, and health.**

**Figure 14.7.** Environmental policies to mitigate emissions will affect both air quality and climate change, and actions can be coordinated to address both problems simultaneously. Blue boxes show mitigation actions aimed at conventional air pollution controls; orange boxes show actions targeted at short-lived climate pollutants; and white boxes show other types of actions. Emissions-reduction actions in the upper right have greater air quality and climate benefits. Box position indicates the relative potential of actions, from most detrimental to most beneficial, and should not be interpreted quantitatively (e.g., that one action has twice the potential of another). The size of the boxes indicates some uncertainty, with actions in boxes straddling an axis being uncertain in the direction of the effect. Addressing climate change requires moving to the actions on the right-hand side of the figure, where many options simultaneously improve air quality. Figure credit: EPA, University of North Carolina at Chapel Hill, and Duke University.

Economy-wide GHG reductions are expected to decrease emissions of air pollutants emitted from the same sources, resulting in benefits for air quality and health (KMs 13.3, 32.4).[226,227,228,229,230] Each metric ton of $CO_2$ reduced is estimated to bring about health benefits[231] that are valued in 26 US studies from $8 to $430 (in 2022 dollars), with a median of $100 per ton of $CO_2$ (see Traceable Accounts for details on relevant studies), mainly from avoided premature death. These health benefits can significantly offset or exceed implementation costs for many GHG mitigation measures (Figure 14.8). Since health benefits exceed costs in most studies, these GHG reductions are economically beneficial, even without accounting for other benefits of slowing climate change. Estimates of these benefits vary across many studies because of differences in mitigation actions considered, methods of assessing emissions, pollutant concentrations and health impacts, and mortality valuation.[232] Most studies have typically evaluated mortality while neglecting morbidity impacts, such as preterm births, restricted activity days, and hospitalizations,[233] and therefore may underestimate the full health benefits of GHG reductions. However, some individual actions, including biomass energy and carbon capture and storage, may provide small air quality benefits or even worsen air quality (Figure 14.7; KM 5.3).[234] Lastly, GHG mitigation policies may alleviate or worsen inequities in air pollution exposure, depending on their design (KMs 14.3, 32.4).

## Air Quality and Health Benefits Estimates in the US, Relative to Costs




**Air quality health benefits alone exceed or significantly offset the costs of greenhouse gas reductions.**

**Figure 14.8.** Controls on greenhouse gas (GHG) emissions also reduce air pollutant emissions from the same sources (often fossil fuel combustion), improving air quality and saving lives. Each circle denotes the results from a study in the US during 2013–2022. These studies find that the value of health benefits significantly offset or in most cases exceed the GHG emissions control costs, apart from other benefits of slowing climate change. Figure credit: EPA, University of North Carolina at Chapel Hill, and Duke University.

The air quality benefits of GHG controls by reducing co-emitted air pollutants occur mainly locally and regionally and nearly immediately following emissions reductions.[19,235] By contrast, benefits of slowing climate change, including lessening the impacts of climate change on air quality (KM 14.1), are long term and distributed globally. Recognizing these air quality health benefits strengthens incentives for local, state, and national actions to reduce GHG emissions.[236]

Indoor air quality can also be affected by GHG reduction actions, as some methods for improving building energy efficiency decrease ventilation, which can increase mold and degrade indoor air quality.[237] Newer approaches to building design improve energy efficiency while meeting temperature control and indoor air quality needs.[238] More widespread application of these approaches can reduce energy use, mitigate GHG emissions, and improve indoor air quality (KM 12.3).

Climate mitigation actions focused on short-lived climate pollutants (SLCPs) can also improve local air quality. Reducing SLCPs, including methane, black carbon, and ozone, directly improves air quality and reduces the near-term rate of warming, affecting climate more quickly than reductions in long-lived GHGs like $CO_2$.[239,240] Methane directly contributes to warming and increases ozone air pollution globally.[42,241] The social cost of methane is estimated at around $2,200 (in 2022 dollars) per metric ton[242] when accounting for impacts via climate change. Other estimates that also include health impacts of ozone are higher (about $4,600 to $9,200 per metric ton in 2022 dollars), with over half of that from ozone health impacts.[243,244,245] VOCs and carbon monoxide (CO) form ozone in the atmosphere, and reducing their emissions benefits both climate and air quality. Nitrogen oxides also contribute to ozone but have a net cooling influence by shortening methane's lifetime and forming $PM_{2.5}$.[240,246] Together, global emissions of methane, VOCs, CO, and black carbon have contributed about 1.5°F to global average warming in 2019, compared to about 1.4°F from $CO_2$ increases (KM 3.1).[247]

Most forms of $PM_{2.5}$ cool the climate, and removing them exacerbates climate warming (KMs 2.1, 3.1), as seen from historical sulfur dioxide reductions to improve air quality.[248,249,250,251] If $PM_{2.5}$ reductions are undertaken together with $CO_2$ and SLCP reductions, this short-term warming may be outweighed, leading to a net cooling.[252,253] Carbon particles, mostly from fires and burning fossil fuels, cause a mix of warming and cooling effects.[240] Of these, black carbon is the component that contributes most to warming, and actions targeting

sources that emit relatively more black carbon, like diesel engines, are expected to best reduce warming while improving air quality. Ammonia, which contributes to $PM_{2.5}$ and is growing in relative importance as a $PM_{2.5}$ source, comes mostly from agriculture.[254] Agricultural ammonia and methane emissions can be reduced by more efficient use of fertilizer[255,256] and adopting healthier plant-based diets.[244,257] Finally, air pollutants can influence regional climate such as through changes in clouds and precipitation, and black carbon can increase snowmelt, which affects water resources (KM 4.1).[258]

# Traceable Accounts

## *Process Description*

Authors were selected to provide diversity in topical focus areas and to align expertise with the anticipated topics for the chapter, as well as for geographic and racial diversity. All authors are recognized experts in climate change and air quality, including in the focus areas of the chapter.

The author team met online roughly every two weeks to discuss the organization of topics, main points to emphasize, and the many logistical questions related to writing the chapter. The author team agreed on five key topics as the focus of the chapter, reflected in the Zero Order Draft (ZOD). The ZOD was made publicly available, and a public engagement workshop was held on January 18, 2022, where the author team gathered public comments on the ZOD. All written public comments on the ZOD were reviewed by the author team, and responses were provided for each. Similarly, the author team responded to comments received on multiple drafts that followed.

Key Messages were developed by small author teams, who were responsible for developing the content of each topic area, and discussed among all authors. The team achieved consensus on the wording of the Key Messages for the Third Order Draft through group meetings to discuss this text specifically. Following comments on drafts of the Fourth Order Draft, the team made small revisions to the Key Messages, and these were discussed among authors to again achieve consensus.

## Key Message 14.1

## Climate Change Will Hamper Efforts to Improve US Air Quality

### Description of Evidence Base

An extensive literature base documents air quality modeling of the response of ozone and fine particulate matter ($PM_{2.5}$) to future climate change. Comparison across studies, however, is challenging due to the use of different scenarios, time periods, metrics, and process representations in the modeling systems. The chemistry of both ozone and $PM_{2.5}$ is complex, which adds to the difficulty of predicting the influence of climate change on air quality. Source gases of ozone and $PM_{2.5}$ include methane, carbon monoxide, nitrogen oxides, non-methane volatile organic compounds, sulfur dioxide, ammonia, and dimethyl sulfide; types of $PM_{2.5}$ directly emitted into the atmosphere include black carbon, organic carbon, mineral dust, sea salt, pollen, and spores.

The literature using observations to infer process-level relationships between air pollutants and climate is growing and includes links with temperature, precipitation, winds, and near-surface mixing.[39,259,260] However, observational records are relatively short (a few decades at best), and isolating responses to meteorology requires disentangling air pollution responses to large emissions perturbations over the observing period to reveal the influence of climate change and variability. Air pollution trends in recent decades in some urban areas and at the regional scale are well established based on high-quality monitoring.[13,261] A large literature base employs a wide range of methods to attribute observed trends and variability to anthropogenic emissions versus meteorological variability. Highly resolved spatial distributions needed to assess community-level exposure are sparse but growing, and new observations from satellites and low-cost sensors will prove useful in this regard. For example, the Tropospheric Emissions: Monitoring of Pollution (TEMPO) satellite instrument, launched in April 2023, promises to provide hourly, fine-spatial information about US pollution.[262,263]

Many processes involving interactions between climate and air quality have been the foci of major lab, field, and modeling efforts (e.g., wildfires) or represent fundamental physics (e.g., the increase in water vapor as temperatures rise), and new work since the Fourth National Climate Assessment (NCA4) was published in 2018 further strengthens this deep evidence base. Such processes and their impacts on air pollution in a changing climate are illustrated in Figure 14.1. Wildfires are a key example of how feedbacks from the biosphere are expected to increase air pollution in future years (KM 14.2).[264] An increased frequency of heatwaves will also lead to more extreme levels of ozone and $PM_{2.5}$ (KM 2.2),[38,265,266] while warmer average temperatures will increase seasonal mean daily maximum 8-hour average (MDA8) ozone and $PM_{2.5}$ concentrations.[49,51,260] The source gases of ozone and $PM_{2.5}$ from plants and soils are expected to increase with warmer and drier conditions,[259,267,268,269] thus degrading air quality. In addition, as plants wither and die during drought, ozone that would otherwise be deposited on leaves may accumulate in the atmosphere,[270,271] although this process is less well studied. Other processes may lead to lower pollution in a warmer climate. Some studies project that annual average precipitation, which removes $PM_{2.5}$, will increase across much of the United States by 2100,[272] but not all studies agree.[273] Basic physics explains why atmospheric humidity will rise with temperature, and the chemical reactions governing ozone destruction will increase with humidity, reducing ozone in unpolluted regions.[68,274] In contrast, greater humidity is expected to worsen $PM_{2.5}$ air quality in some regions.[275] Finally, future trends in the regional transport of pollution or in the frequency of weather patterns like stagnation will have consequences for US air pollution, but these trends are not well established across the US.[276,277,278]

Efforts to model the net response of US air quality to climate change have taken two main approaches, with some studies focusing on the impact from climate change alone[27,41,49,50,51,52,68,279] and other studies including the influences of both climate change and changing emissions from human sources of ozone and $PM_{2.5}$, such as fossil fuel combustion.[26,39,45,67] Some studies compare the combined effects of emissions and climate change with climate change alone.[44,46] There is general agreement across these studies that climate change will degrade US air quality in many regions with high concentrations of pollutants. Summertime average surface ozone is expected to increase across much of the northern and eastern United States[26,51] and during heatwaves in populous areas already affected by pollution.[53] Surface $PM_{2.5}$ is also projected to increase in areas prone to wildfires (KM 14.2) or dust events,[63] but there is less agreement on the response of $PM_{2.5}$ elsewhere.[50,51,54,280]

Many epidemiological health studies have identified a wide range of adverse health outcomes following exposure to wildfire smoke and dust, as well as to ozone and particulate matter. Such adverse outcomes are expected to generally increase in response to ongoing climate change.[26]

## Major Uncertainties and Research Gaps

Uncertainties remain in how meteorology will respond to climate change in different regions of the United States and how these meteorological responses, in turn, will trigger changes in different air pollutants. While it is well established that rising methane will increase background ozone at the surface, there is uncertainty in the spatial patterns of this response tied to nitrogen oxides emissions, including from ship plumes.[42,281] Climate variability tends to dominate the uncertainty in shorter-range projections (thin lines in Figure 14.2).[282,283,284] Health responses to the combined impacts of exposure to multiple pollutants and other climate change impacts (heat, flooding) are not well quantified. Extensive research into the relative toxicity of $PM_{2.5}$ mixtures has not consistently shown that any particular source or component is more strongly related to health effects than total $PM_{2.5}$ mass.[285]

The lack of systematic information available from chemistry–climate models for US air quality complicates the assessment of future change. For example, Figure 14.2 makes use of the most comprehensive set of coordinated simulations with international climate models that include the atmospheric chemistry necessary for projections of future air quality. There are different numbers of models with simulations

available for each scenario. Specifically, seven models simulated $PM_{2.5}$ for both the historical simulations and four future air pollutant emissions and climate scenarios during 2015–2100 (see Table 3 in the Guide to the Report). In contrast, for ground-level ozone, fewer models (one to five depending on scenario) archived the hourly ground-level ozone needed to calculate the MDA8 metric used to assess compliance with the National Ambient Air Quality Standards. In Figure 14.2, thick lines show the average of all available model simulations for each scenario, with each simulation shown individually by the thin lines. A list of the individual models that produced each scenario in Figure 14.2, together with the simulated fields, are available in the metadata. Models and simulations are further described by Turnock et al. (2020).[15]

In more recent studies, progress is being made in quantifying different sources of uncertainty in emissions scenarios and future projections for US air quality, including separately determining the uncertainty associated with model mechanisms and with naturally arising climate variability.[259,286,287]

### Description of Confidence and Likelihood

The overall assessment of *medium confidence* that climate change is projected to worsen US air quality in many US regions reflects uncertainty in the net ozone and $PM_{2.5}$ responses to climate change across different regions.[48,49,50,51,54,68,280] The evidence for air pollution impacts on health is well established from epidemiological and toxicological studies,[4,7,9,10] supporting a *very likely*, *high confidence* assessment. There is *very high confidence* and it is *very likely* that climate change will increase the intensity and frequency of extreme heat (KM 2.2).[247] Observational evidence, theoretical understanding, and modeling studies all support an assessment of *high confidence* that increasing frequency of warmer and drier conditions will *very likely* raise the risk of exposure to airborne dust and wildfire smoke in some regions.[62,63,69,288]

## Key Message 14.2

## Increasing Wildfire Smoke Is Harming Human Health and Catalyzing New Protection Strategies

### Description of Evidence Base

This section was based on a review of the recent peer-reviewed literature. Many studies detail the harmful health effects of wildfire smoke on human health. A growing weight of evidence indicates that wildfires and associated air quality impacts will increase in the future with a warming climate, but the interactions are complex and regionally driven. Our understanding of smoke exposure and health impacts has been aided by combinations of surface and satellite-based observations, as well as model simulations.[289,290] Smoke prediction (forecast) systems are a useful mitigation tool,[121] and the number of them online, along with many science improvements, has grown in recent years across North America.[112,114,115,291,292,293,294]

Since NCA4, particularly impactful wildfire smoke years have driven the development of new communication and smoke mitigation measures. The authors highlight the growing base of information on how the public can protect itself before and during a wildfire, such as that found in the EPA Smoke-Ready Toolbox (https://www.epa.gov/smoke-ready-toolbox-wildfires), as well as the development of wildfire smoke mitigation programs by many states and Tribes, in addition to federal programs.[295,296,297,298] Evidence shows that social media plays an important role in communicating mitigation measures. For example, smoke blogs in many western states are a nexus of information.[299,300,301,302]

### Major Uncertainties and Research Gaps

Uncertainties in future smoke exposure are intrinsically tied to the uncertainties in future wildfires. Hence, improvements in future wildfire projections will reduce uncertainties in future smoke exposure. Related to this is the uncertainty regarding how future use of prescribed fire as a management tool for wildfire

mitigation and ecosystem health will affect smoke at regional and national extents. Finally, quantification of how Indigenous fire practices influence smoke both historically and into the future will also reduce this uncertainty.

Uncertainties remain in our understanding of the health effects of smoke-specific particulate matter and the impacts of cumulative smoke exposure over many years. Research investigating indoor concentrations during wildfire smoke events is preliminary, and there is a specific need to understand how indoor concentrations vary between socioeconomic groups during wildfire smoke events. Research quantifying the effectiveness of smoke mitigation measures and other health protection interventions is limited, and relying on personal interventions such as wearing face masks, filtering indoor air, and staying indoors can have limitations.[303,304]

### Description of Confidence and Likelihood

There is *very high confidence* that wildfires emit gases and fine particulate matter that are harmful to human health based on epidemiological and toxicological studies.[74,77,88,89,90,91,92,93,94,95] Many studies document the effects of short-term acute exposures on respiratory healthcare outcomes (Liu et al. 2015; Reid et al. 2016[92,93] and references therein). Less quantified but also of concern are the effects of long-term lower-level exposure.[92,93] A growing weight of evidence supports the *likely*, *high confidence* assessment that with a warming climate, wildfires and associated air quality impacts will increase in the future in many regions of the contiguous US and Alaska, but the fire-climate interactions are complex and regionally driven, and the extent to which human management actions will influence future wildfire activity is unknown (Ch. 7). Since NCA4, particularly impactful wildfire smoke years have driven the development of new communication and smoke mitigation measures.[117,118,119,120,121] Advancements in the science in models and observational data are also leading to products to help inform the public.[112,113,114,115,116,154] However, these developments may not be enough to substantially reduce exposure, especially for all demographic groups.[125,126] This uncertainty in exposure reduction leads to the assessment of *medium confidence* in the efficacy of these measures and the conclusion that challenges remain.

## Key Message 14.3

## Air Pollution Is Often Worse in Communities of Color and Low-Income Communities

### Description of Evidence Base

This section is based on a review of peer-reviewed scientific literature, focusing on work published in the last decade. It has been repeatedly shown that communities of color, low-income communities, and other marginalized groups are disproportionately exposed to and harmed by air pollution.[25,30,132,133,134,135,136,137,138,139,140,141,142,143,144,145,146,147,148,152,153,154,155] Over the last 10 years, there has been an emphasis on developing and applying new measurements and models to describe air pollution inequalities and, in some cases, on deepening commitments to community-engaged scholarship. Improved monitoring and modeling have advanced tools for distinguishing pollutant differences within and between neighborhoods, whereas research over previous decades was largely based on analyses of source proximity and/or health impacts. A new generation of sensors, costing a few hundred dollars each, is supporting collaborative air quality and exposure research and producing actionable results.[305,306,307,308,309,310,311] In addition, recent advances in satellite remote sensing are enabling more detailed observations of neighborhood-level pollution inequalities, with satellite measurements being used directly in the case of nitrogen dioxide ($NO_2$)[138,163,177,312] and in combination with models for $PM_{2.5}$ and $NO_2$,[133,134,135,313,314] with additional information, especially on daytime temporal variability, anticipated with the launch of TEMPO. Machine learning and regression models are filling observational gaps and improving estimates of unequal exposures.[129,134,313,315] Current understanding of air pollution health

impact disparities is also improving through neighborhood-level datasets on disease rates.[133,314] Chemical transport models, which are standard research and air quality decision-making tools that account for key chemical and physical processes, have only begun to be used for neighborhood-level environmental justice applications because of model resolution challenges.[316,317] That said, neighborhoods are typically larger than the spatial gradients of primary pollutants, and emissions sources are often clustered in overburdened communities. As a result, models with very-fine-scale spatial resolution (hundreds of meters) may not always be needed to describe neighborhood-level inequalities,[163,318] further opening the range of tools applicable to describing and understanding air pollution inequalities. As air pollution datasets evolve, they reinforce what communities with environmental justice concerns have been saying for decades.

## Major Uncertainties and Research Gaps

While patterns of inequities related to air pollution sources, exposure, and associated adverse health impacts are well established, we lack tools that fully describe neighborhood-level distributions of a wide variety of pollutants harmful to health, such as air toxins, and of pollutant mixtures. Air pollution exposures also occur in the home, in classrooms, and at work, and there is little research simultaneously considering outdoor, indoor, and occupational exposures. To date, researchers have largely focused on producing high spatial resolution air pollution maps, and as a result, there is far less knowledge of the temporal variability and source patterns driving air pollution inequalities. Without also capturing this temporal variability, it is difficult to incorporate issues of inequalities in broader air quality and climate change decision-making.[163] Equity-related questions are not a common feature of air pollution–climate research, partly because of computational limitations on model spatial resolution and partly because of disciplinary and regulatory divides in the fields of air quality and environmental justice. There is limited research on how greenhouse gas (GHG) mitigation actions have differential impacts on air quality affecting different communities, but there is clear evidence that without considering equity, GHG regulations can adversely affect air quality in communities of color and communities with low-socioeconomic status.[168]

## Description of Confidence and Likelihood

There is *very high confidence* that communities of color, low-income communities, and other marginalized populations, on average, live in greater proximity to emissions sources, experience higher levels of air pollution, and are disproportionately harmed by poor air quality[25,129,138,152,153,319]—this has been repeatedly shown for decades. The author team assigns *very likely, high confidence* to the statement that these same communities will disproportionately face worsened cumulative air pollution burdens from climate change–driven hazards. Regarding the likelihood, there are two facets to consider concerning how climate change will affect air pollution inequity: 1) how the amount and distribution of air pollution will differ in the future and 2) how the health impacts of air pollution exposures will vary with climate change. There is less research on how the amount and distribution of air quality (i.e., air pollution inequalities) will change in the future,[155,163] with varying effects possible depending on which control strategies are employed and whether pollutants are directly emitted into the atmosphere or formed in the atmosphere through chemistry. The likelihood and confidence statements are largely based on the second facet—because of well-documented inequalities in the distribution of other climate-sensitive environmental benefits and harms (KMs 9.2, 12.2, 15.2) and because of other forms of structural racism affecting the impacts of air pollution on health and well-being,[152,156] hence the *high confidence.* The cumulative burdens of air pollution with other climate change-driven hazards are *very likely* to increase in the coming decades in the absence of equity-focused emission controls. The author team assigns *high confidence* to the statement that equity-focused decision-making is critical for reducing air pollution inequities, as it has been borne out over decades of improved air quality across the US that air pollution disparities persist.[132,133,134,135,136,137] Sector, market, and pollutant threshold-based controls have been shown to have smaller equity benefits than location-specific interventions,[169] with California's GHG market serving as a real-world demonstration that GHG controls have the potential to worsen air pollution inequalities.[168]

## Key Message 14.4

# Climate Change Is Worsening Pollen Exposures and Adversely Impacting Health

### Description of Evidence Base

This section was based on a review of the recent peer-reviewed literature. A large number of articles using new data and tools have been published in the past few years, and some have provided insight into the attribution of observed shifts in pollen metrics to anthropogenic climate change.

Recent developments have enhanced our understanding of climatic influences on pollen. These include improved understanding of plant phenology,[203,320,321,322,323] improved measurements of aeroallergen concentrations,[194,201,324] new modeling platforms for pollen emissions and transport,[204,205,207,325,326] novel analytics tools for recognizing pollen patterns,[327,328] automatic analysis of pollen types,[329,330] and remotely sensed data on meteorology, air quality, and phenology.[321,331,332] In addition to these methodological advances that allow for greater insight into factors influencing aeroallergen distribution and concentration, climatic influences are becoming clearer as the climate shifts further, and longer time series allow for greater confidence in the correlations observed.

Strategies for reducing the impact of allergic airway disease by avoiding and reducing pollen exposure,[213] which can be facilitated through public health campaigns[214] and taking medications to reduce immune response intensity,[212] have been established for years. More recent literature has highlighted gaps in diagnosing and treating allergic airway disease.[211]

### Major Uncertainties and Research Gaps

There are several papers suggesting overall trends in pollen season and concentrations for total pollen and ragweed, but there is limited evidence for specific taxa, and there is less literature on climate change impacts on indoor and outdoor mold exposure. There is also limited evidence linking changes in health impacts with changes in exposure; however, there is abundant evidence that allergic respiratory disease is driven by exposure, so there is a strong presumption of a link. There is relatively limited information on the health equity impacts of changes in pollen exposure and on the effectiveness of early warning systems in reducing symptom burden. Lastly, there is little information quantifying the likelihood that investments in adaptation can fully close the adaptation gap and negate climate change–attributable shifts in allergic airway disease.

### Description of Confidence and Likelihood

There is *very high confidence* in the linkage between aeroallergen exposure and the development and intermittent exacerbation of allergic airway disease and, by extension, that increased aeroallergen exposure damages the health of people who suffer from allergic airway disease.[185,186,187,188,189,190,192] There is *high confidence* and it is *very likely* that human-caused climate change, particularly warming, has already changed the patterns of pollen seasons based on both observational studies in North America as well as modeling studies assessing the influence of anthropogenic climate change compared against a counterfactual without anthropogenic climate forcing (Figure 14.6).[187,194,196,198,199,200,201] This evidence demonstrates that shifts in pollen concentrations vary by region. There is *high confidence* and it is *very likely* that as the climate changes further, these trends will continue and that further shifts in aeroallergen concentrations and distribution will depend on the rate at which the climate changes and, in particular, the rate of warming in a given location (Figure 14.6).[204,206,207,208,210] Based on past experience with managing allergic airway disease, there is *high confidence* that the health impacts associated with increased pollen from climate change can be counteracted fully or in part through improvements including increasing access to allergists, improved diagnosis and disease management, and allergy early warning systems.[211,212,213,214]

## Key Message 14.5

### Policies Can Reduce Greenhouse Gas Emissions and Improve Air Quality Simultaneously

#### Description of Evidence Base

The author team made use of the existing literature, emphasizing studies published since NCA4 but also referencing some classic papers published before 2018. The author team emphasizes here how decisions to control GHG emissions often have effects on air pollutant emissions. Similarly, decisions to control air pollutant emissions may influence GHG emissions. The author team therefore highlights the opportunity to control both types of emissions simultaneously through reductions in fossil fuels use, addressing both air pollution and climate change. Conclusions are informed by historical changes in emissions in the US and elsewhere, particularly the actions to implement air quality regulations through controls on smokestack emissions from power plants and large industries and controls on tailpipe emissions from motor vehicles. A fuller array of possible actions is presented in Figure 14.7, which emphasizes the capacity for actions to affect emissions of both air pollutants and GHGs in the near-term (targeting 2030), without explicit consideration for the cost-effectiveness of actions. Figure 14.7 does not present the potential for emissions reductions quantitatively, as the author team is not aware that this has been analyzed previously for the US. Rather the author team used information from several key sources to inform where boxes are placed in Figure 14.7, including US emissions inventories for GHGs[215] and air pollutants,[333] which constrain the potential reductions of some actions. Estimates of the global GHG mitigation capacity from the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) Working Group III[221] help quantify the capacity for reduction, although these estimates are not specifically for the US, and estimates specifically for US energy system actions are from Figure 32.22. Estimates of sector contributions to US air pollution–related deaths[216] are also used, as are qualitative estimates of the effects of GHG reductions on air pollution in the United Kingdom.[65] Using these sources of information, emissions-reduction actions are put in order separately along the two axes in Figure 14.7 and then plotted. In some cases, minor changes in the order are made to fit the boxes on the figure. The boxes themselves are intended to communicate that there is some uncertainty in the emissions reductions, including boxes that straddle an axis, indicating uncertainty in the sign of the influence. Box positions should not be interpreted quantitatively (e.g., inferring that emissions-reduction capacity for one action is twice that of another action). Actions considered include those emphasized in past emissions reductions and considered for future action in the US, and not all possible actions can be included here. The analysis also focuses on technology actions rather than policy approaches (cap-and-trade, incentives for clean technology) used to achieve these goals.

There are many studies of the air quality and human health benefits due to the co-pollutant emission reductions from GHG mitigation actions.[226,227,228,229,230,231] The author team surveyed the literature and found 26 studies that either directly reported or contained enough information to quantify the monetary value of human health benefits from improved air quality per ton of mitigated GHG emissions. In some cases, it was necessary to contact the authors to ensure that the data were being interpreted correctly. These 26 studies form the basis of the range presented in the text ($8 to $430 in 2022 dollars, with a median of $100 per metric ton of $CO_2$). The estimates of human health benefits and costs from these studies span a range of two orders of magnitude because of different methods used, geographical scope, time periods analyzed, and GHG reduction actions considered. Figure 14.8 presents results from the subset of these studies that included both the air quality human health benefits and GHG mitigation costs. A complete list of the 26 studies and their reported values is available in the metadata for Figure 14.8.

Discussion of short-lived climate pollutants has a strong foundation in past research, as summarized in the IPCC AR6,[240] although some significant uncertainties remain in the magnitude of global anthropogenic radiative forcing for some of these species and in the net effects on climate from reductions of short-lived climate pollutants[252] in the United States in particular.

On the subject of social costs, since this chapter is about the link between climate change and air quality, it seemed appropriate to use costs that include both climate change and air pollution.[244] As the text states, "over half of [the value is] from ozone health impacts," so it is clear that this differs from commonly used costs, such as those produced by the US Government's Interagency Working Group on the Social Cost of Greenhouse Gases for use in regulations, which include only damages related to climate changes.[334]

## Major Uncertainties and Research Gaps

Whereas there are new global modeling studies estimating air pollutant concentrations in future Shared Socioeconomic Pathway (SSP) scenarios, including the impacts of climate change on air quality, no study has yet downscaled these simulations to the United States for studying air pollution impacts. There is a gap in research that critically assesses how air pollution is projected to change in the US under scenarios that lead to decarbonization and approach net-zero emissions. There is also limited research in quantifying the effects of actions considered on both GHG and air pollutant emissions, as well as their costs and potential for emissions reductions, since much of the literature available focuses on GHG reductions without estimates of concurrent air pollutant emissions reductions.

## Description of Confidence and Likelihood

There is *high confidence* and it is *very likely* that broad policies to reduce greenhouse gas emissions economy-wide in the United States will reduce air pollutant emissions and benefit air quality and health, although some individual actions may not achieve these benefits (Figure 14.7).[227,230,231] Many studies have estimated the air quality and human health benefits of greenhouse gas reduction actions, most of which have found that monetized benefits exceed the costs of greenhouse gas controls (see Figure 14.8 and associated metadata), when premature mortality is monetized using methods commonly used in the United States,[22] such as those used by the EPA. Therefore, there is *high confidence* that monetized health benefits would exceed costs for many greenhouse gas reduction actions, and it is *likely* that many specific actions will also have health benefits exceeding costs.[19,226,229] Based on several individual studies, there is *high confidence* that pursuing actions that emphasize reduced fossil fuel use, improved energy efficiency, and reductions in short-lived climate pollutants would not only put the United States on a trajectory that would substantially reduce GHG emissions and approach net-zero emissions (KM 32.4) but also substantially improve air quality and health.[224,231]

# References


1. EPA, 2020: Integrated Science Assessment (ISA) for Ozone and Related Photochemical Oxidants (Final Report, Apr 2020). EPA/600/R-20/012. U.S. Environmental Protection Agency, Washington, DC. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=348522

2. Turner, M.C., M. Jerrett, C.A. Pope, D. Krewski, S.M. Gapstur, W.R. Diver, B.S. Beckerman, J.D. Marshall, J. Su, D.L. Crouse, and R.T. Burnett, 2016: Long-term ozone exposure and mortality in a large prospective study. *American Journal of Respiratory and Critical Care Medicine*, **193** (10), 1134–1142. https://doi.org/10.1164/rccm.201508-1633oc

3. Emberson, L., 2020: Effects of ozone on agriculture, forests and grasslands. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **378** (2183), 20190327. https://doi.org/10.1098/rsta.2019.0327

4. Bell, M.L., K. Ebisu, B.P. Leaderer, J.F. Gent, H.J. Lee, P. Koutrakis, Y. Wang, F. Dominici, and R.D. Peng, 2014: Associations of $PM_{2.5}$ constituents and sources with hospital admissions: Analysis of four counties in Connecticut and Massachusetts (USA) for persons ≥ 65 years of age. *Environmental Health Perspectives*, **122** (2), 138–144. https://doi.org/10.1289/ehp.1306656

5. Calderón-Garcidueñas, L. and A. Ayala, 2022: Air pollution, ultrafine particles, and your brain: Are combustion nanoparticle emissions and engineered nanoparticles causing preventable fatal neurodegenerative diseases and common neuropsychiatric outcomes? *Environmental Science & Technology*, **56** (11), 6847–6856. https://doi.org/10.1021/acs.est.1c04706

6. Dockery, D.W., F.E. Speizer, D.O. Stram, J.H. Ware, J.D. Spengler, and B.G. Ferris, 1989: Effects of inhalable particles on respiratory health of children. *American Review of Respiratory Disease*, **139** (3), 587–594. https://doi.org/10.1164/ajrccm/139.3.587

7. Johnson, N.M., A.R. Hoffmann, J.C. Behlen, C. Lau, D. Pendleton, N. Harvey, R. Shore, Y. Li, J. Chen, Y. Tian, and R. Zhang, 2021: Air pollution and children's health—A review of adverse effects associated with prenatal exposure from fine to ultrafine particulate matter. *Environmental Health and Preventive Medicine*, **26** (1), 72. https://doi.org/10.1186/s12199-021-00995-5

8. Krewski, D., M. Jerrett, R.T. Burnett, R. Ma, E. Hughes, Y. Shi, M.C. Turner, C.A. Pope, III, G. Thurston, E.E. Calle, and M.J. Thun, 2009: Extended Follow-up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality. HEI Research Report 140. Health Effects Institute, Boston, MA, 140 pp. https://pubmed.ncbi.nlm.nih.gov/19627030/

9. Ljungman, P.L.S., N. Andersson, L. Stockfelt, E.M. Andersson, J.N. Sommar, K. Eneroth, L. Gidhagen, C. Johansson, A. Lager, K. Leander, P. Molnar, N.L. Pedersen, D. Rizzuto, A. Rosengren, D. Segersson, P. Wennberg, L. Barregard, B. Forsberg, G. Sallsten, T. Bellander, and G. Pershagen, 2019: Long-term exposure to particulate air pollution, black carbon, and their source components in relation to ischemic heart disease and stroke. *Environmental Health Perspectives*, **127** (10), 107012. https://doi.org/10.1289/ehp4757

10. Yitshak-Sade, M., I. Kloog, J.D. Schwartz, V. Novack, O. Erez, and A.C. Just, 2021: The effect of prenatal temperature and $PM_{2.5}$ exposure on birthweight: Weekly windows of exposure throughout the pregnancy. *Environment International*, **155**, 106588. https://doi.org/10.1016/j.envint.2021.106588

11. Hopke, P.K., Q. Dai, L. Li, and Y. Feng, 2020: Global review of recent source apportionments for airborne particulate matter. *Science of The Total Environment*, **740**, 140091. https://doi.org/10.1016/j.scitotenv.2020.140091

12. Wells, B., P. Dolwick, B. Eder, M. Evangelista, K. Foley, E. Mannshardt, C. Misenis, and A. Weishampel, 2021: Improved estimation of trends in U.S. ozone concentrations adjusted for interannual variability in meteorological conditions. *Atmospheric Environment*, **248**, 118234. https://doi.org/10.1016/j.atmosenv.2021.118234

13. EPA, 2022: Our Nation's Air: Trends Through 2020. U.S. Environmental Protection Agency. https://gispub.epa.gov/air/trendsreport/2021

14. EPA, 2022: Policy Assessment for the Reconsideration of the National Ambient Air Quality Standards for Particulate Matter. EPA-452/R-22-004. U.S. Environmental Protection Agency, Research Triangle Park, NC. https://www.epa.gov/system/files/documents/2022-05/Final%20Policy%20Assessment%20for%20the%20Reconsideration%20of%20the%20PM%20NAAQS_May2022_0.pdf

15. Turnock, S.T., R.J. Allen, M. Andrews, S.E. Bauer, M. Deushi, L. Emmons, P. Good, L. Horowitz, J.G. John, M. Michou, P. Nabat, V. Naik, D. Neubauer, F.M. O'Connor, D. Olivié, N. Oshima, M. Schulz, A. Sellar, S. Shim, T. Takemura, S. Tilmes, K. Tsigaridis, T. Wu, and J. Zhang, 2020: Historical and future changes in air pollutants from CMIP6 models. *Atmospheric Chemistry and Physics*, **20** (23), 14547–14579. https://doi.org/10.5194/acp-20-14547-2020

16. Murray, C.J.L., A.Y. Aravkin, P. Zheng, C. Abbafati, K.M. Abbas, et al., 2020: Global burden of 87 risk factors in 204 countries and territories, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, **396** (10258), 1223–1249. https://doi.org/10.1016/s0140-6736(20)30752-2

17. Burnett, R., H. Chen, M. Szyszkowicz, N. Fann, B. Hubbell, C.A. Pope, J.S. Apte, M. Brauer, A. Cohen, S. Weichenthal, J. Coggins, Q. Di, B. Brunekreef, J. Frostad, S.S. Lim, H. Kan, K.D. Walker, G.D. Thurston, R.B. Hayes, C.C. Lim, M.C. Turner, M. Jerrett, D. Krewski, S.M. Gapstur, W.R. Diver, B. Ostro, D. Goldberg, D.L. Crouse, R.V. Martin, P. Peters, L. Pinault, M. Tjepkema, A. van Donkelaar, P.J. Villeneuve, A.B. Miller, P. Yin, M. Zhou, L. Wang, N.A.H. Janssen, M. Marra, R.W. Atkinson, H. Tsang, T.Q. Thach, J.B. Cannon, R.T. Allen, J.E. Hart, F. Laden, G. Cesaroni, F. Forastiere, G. Weinmayr, A. Jaensch, G. Nagel, H. Concin, and J.V. Spadaro, 2018: Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (38), 9592–9597. https://doi.org/10.1073/pnas.1803222115

18. Seltzer, K.M., D.T. Shindell, and C.S. Malley, 2018: Measurement-based assessment of health burdens from long-term ozone exposure in the United States, Europe, and China. *Environmental Research Letters*, **13** (10), 104018. https://doi.org/10.1088/1748-9326/aae29d

19. Shindell, D., M. Ru, Y. Zhang, K. Seltzer, G. Faluvegi, L. Nazarenko, G.A. Schmidt, L. Parsons, A. Challapalli, L. Yang, and A. Glick, 2021: Temporal and spatial distribution of health, labor, and crop benefits of climate change mitigation in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (46), e2104061118. https://doi.org/10.1073/pnas.2104061118

20. Vohra, K., A. Vodonos, J. Schwartz, E.A. Marais, M.P. Sulprizio, and L.J. Mickley, 2021: Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. *Environmental Research*, **195**, 110754. https://doi.org/10.1016/j.envres.2021.110754

21. EPA, 2023: Environmental Benefits Mapping and Analysis Program—Community Edition, User Manual. U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-04/documents/benmap-ce_user_manual_march_2015.pdf

22. EPA, 2023: Estimating $PM_{2.5}$- and Ozone-Attributable Health Benefits, Technical Support Document for the 2022 $PM_{2.5}$ NAAQS Reconsideration Proposal RIA. EPA-HQ-OAR-2019-0587. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2021-10/source-apportionment-tsd-oct-2021_0.pdf

23. McGrath, J.M., A.M. Betzelberger, S. Wang, E. Shook, X.-G. Zhu, S.P. Long, and E.A. Ainsworth, 2015: An analysis of ozone damage to historical maize and soybean yields in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (46), 14390–14395. https://doi.org/10.1073/pnas.1509777112

24. Marlier, M.E., K.I. Brenner, J.C. Liu, L.J. Mickley, S. Raby, E. James, R. Ahmadov, and H. Riden, 2022: Exposure of agricultural workers in California to wildfire smoke under past and future climate conditions. *Environmental Research Letters*, **17** (9), 094045. https://doi.org/10.1088/1748-9326/ac8c58

25. Tessum, C.W., D.A. Paolella, S.E. Chambliss, J.S. Apte, J.D. Hill, and J.D. Marshall, 2021: $PM_{2.5}$ polluters disproportionately and systemically affect people of color in the United States. *Science Advances*, **7** (18), 4491. https://doi.org/10.1126/sciadv.abf4491

26. Fann, N.L., C.G. Nolte, M.C. Sarofim, J. Martinich, and N.J. Nassikas, 2021: Associations between simulated future changes in climate, air quality, and human health. *JAMA Network Open*, **4** (1), e2032064. https://doi.org/10.1001/jamanetworkopen.2020.32064

27. Saari, R.K., Y. Mei, E. Monier, and F. Garcia-Menendez, 2019: Effect of health-related uncertainty and natural variability on health impacts and cobenefits of climate policy. *Environmental Science & Technology*, **53** (3), 1098–1108. https://doi.org/10.1021/acs.est.8b05094

28. Bell, M.L., A. McDermott, S.L. Zeger, J.M. Samet, and F. Dominici, 2004: Ozone and short-term mortality in 95 US urban communities, 1987-2000. *JAMA: The Journal of the American Medical Association*, **292** (19), 2372–2378. https://doi.org/10.1001/jama.292.19.2372

29. Chen, K., K. Wolf, S. Breitner, A. Gasparrini, M. Stafoggia, E. Samoli, Z.J. Andersen, G. Bero-Bedada, T. Bellander, F. Hennig, B. Jacquemin, J. Pekkanen, R. Hampel, J. Cyrys, A. Peters, and A. Schneider, 2018: Two-way effect modifications of air pollution and air temperature on total natural and cardiovascular mortality in eight European urban areas. *Environment International*, **116**, 186–196. https://doi.org/10.1016/j.envint.2018.04.021

30. Kioumourtzoglou, M.A., J. Schwartz, P. James, F. Dominici, and A. Zanobetti, 2016: $PM_{2.5}$ and mortality in 207 US cities: Modification by temperature and city characteristics. *Epidemiology*, **27** (2), 221–227. https://doi.org/10.1097/ede.0000000000000422

31. Yitshak-Sade, M., J.F. Bobb, J.D. Schwartz, I. Kloog, and A. Zanobetti, 2018: The association between short and long-term exposure to $PM_{2.5}$ and temperature and hospital admissions in New England and the synergistic effect of the short-term exposures. *Science of The Total Environment*, **639**, 868–875. https://doi.org/10.1016/j.scitotenv.2018.05.181

32. Zanobetti, A. and A. Peters, 2015: Disentangling interactions between atmospheric pollution and weather. *Journal of Epidemiology and Community Health*, **69** (7), 613–615. https://doi.org/10.1136/jech-2014-203939

33. Kerr, G.H., D.W. Waugh, S.D. Steenrod, S.A. Strode, and S.E. Strahan, 2020: Surface ozone-meteorology relationships: Spatial variations and the role of the jet stream. *Journal of Geophysical Research: Atmospheres*, **125** (21), e2020JD032735. https://doi.org/10.1029/2020jd032735

34. Kerr, G.H., D.W. Waugh, S.A. Strode, S.D. Steenrod, L.D. Oman, and S.E. Strahan, 2019: Disentangling the drivers of the summertime ozone-temperature relationship over the United States. *Journal of Geophysical Research: Atmospheres*, **124** (19), 10503–10524. https://doi.org/10.1029/2019jd030572

35. Previdi, M. and A.M. Fiore, 2019: The importance of sampling variability in assessments of ENSO-$PM_{2.5}$ relationships: A case study for the south central United States. *Geophysical Research Letters*, **46** (12), 6878–6884. https://doi.org/10.1029/2019gl082250

36. Sun, W., P. Hess, G. Chen, and S. Tilmes, 2019: How waviness in the circulation changes surface ozone: A viewpoint using local finite-amplitude wave activity. *Atmospheric Chemistry and Physics*, **19** (20), 12917–12933. https://doi.org/10.5194/acp-19-12917-2019

37. Leibensperger, E.M., L.J. Mickley, and D.J. Jacob, 2008: Sensitivity of US air quality to mid-latitude cyclone frequency and implications of 1980–2006 climate change. *Atmospheric Chemistry and Physics*, **8** (23), 7075–7086. https://doi.org/10.5194/acp-8-7075-2008

38. Schnell, J.L. and M.J. Prather, 2017: Co-occurrence of extremes in surface ozone, particulate matter, and temperature over eastern North America. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (11), 2854–2859. https://doi.org/10.1073/pnas.1614453114

39. Zhang, J., Y. Gao, K. Luo, L.R. Leung, Y. Zhang, K. Wang, and J. Fan, 2018: Impacts of compound extreme weather events on ozone in the present and future. *Atmospheric Chemistry and Physics*, **18** (13), 9861–9877. https://doi.org/10.5194/acp-18-9861-2018

40. Trail, M., A.P. Tsimpidi, P. Liu, K. Tsigaridis, J. Rudokas, P. Miller, A. Nenes, Y. Hu, and A.G. Russell, 2014: Sensitivity of air quality to potential future climate change and emissions in the United States and major cities. *Atmospheric Environment*, **94**, 552–563. https://doi.org/10.1016/j.atmosenv.2014.05.079

41. Zhang, Y. and Y. Wang, 2016: Climate-driven ground-level ozone extreme in the fall over the southeast United States. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (36), 10025–10030. https://doi.org/10.1073/pnas.1602563113

42. Butler, T., A. Lupascu, and A. Nalam, 2020: Attribution of ground-level ozone to anthropogenic and natural sources of nitrogen oxides and reactive carbon in a global chemical transport model. *Atmospheric Chemistry and Physics*, **20** (17), 10707–10731. https://doi.org/10.5194/acp-20-10707-2020

43. Fiore, A.M., D.J. Jacob, B.D. Field, D.G. Streets, S.D. Fernandes, and C. Jang, 2002: Linking ozone pollution and climate change: The case for controlling methane. *Geophysical Research Letters*, **29** (19), 25-1–25-4. https://doi.org/10.1029/2002gl015601

44. Clifton, O.E., A.M. Fiore, G. Correa, L.W. Horowitz, and V. Naik, 2014: Twenty-first century reversal of the surface ozone seasonal cycle over the northeastern United States: Reversal of the NE US high-$O_3$ season. *Geophysical Research Letters*, **41** (20), 7343–7350. https://doi.org/10.1002/2014gl061378

45. Gao, Y., J.S. Fu, J.B. Drake, J.F. Lamarque, and Y. Liu, 2013: The impact of emission and climate change on ozone in the United States under representative concentration pathways (RCPs). *Atmospheric Chemistry and Physics*, **13** (18), 9607–9621. https://doi.org/10.5194/acp-13-9607-2013

46. Rieder, H.E., A.M. Fiore, O.E. Clifton, G. Correa, L.W. Horowitz, and V. Naik, 2018: Combining model projections with site-level observations to estimate changes in distributions and seasonality of ozone in surface air over the U.S.A. *Atmospheric Environment*, **193**, 302–315. https://doi.org/10.1016/j.atmosenv.2018.07.042

47. Jerrett, M., R.T. Burnett, C.A. Pope, K. Ito, G. Thurston, D. Krewski, Y. Shi, E. Calle, and M. Thun, 2009: Long-term ozone exposure and mortality. *The New England Journal of Medicine*, **360** (11), 1085–1095. https://doi.org/10.1056/nejmoa0803894

48. Lu, X., L. Zhang, and L. Shen, 2019: Meteorology and climate influences on tropospheric ozone: A review of natural sources, chemistry, and transport patterns. *Current Pollution Reports*, **5** (4), 238–260. https://doi.org/10.1007/s40726-019-00118-3

49. Shen, L., L.J. Mickley, and L.T. Murray, 2017: Influence of 2000–2050 climate change on particulate matter in the United States: Results from a new statistical model. *Atmospheric Chemistry and Physics*, **17** (6), 4355–4367. https://doi.org/10.5194/acp-17-4355-2017

50. Silva, R.A., J.J. West, J.-F. Lamarque, D.T. Shindell, W.J. Collins, G. Faluvegi, G.A. Folberth, L.W. Horowitz, T. Nagashima, V. Naik, Steven T. Rumbold, K. Sudo, T. Takemura, D. Bergmann, P. Cameron-Smith, R.M. Doherty, B. Josse, I.A. MacKenzie, David S. Stevenson, and G. Zeng, 2017: Future global mortality from changes in air pollution attributable to climate change. *Nature Climate Change*, **7** (9), 647–651. https://doi.org/10.1038/nclimate3354

51. Nolte, C.G., T.L. Spero, J.H. Bowden, M.S. Mallard, and P.D. Dolwick, 2018: The potential effects of climate change on air quality across the conterminous US at 2030 under three Representative Concentration Pathways. *Atmospheric Chemistry and Physics*, **18** (20), 15471–15489. https://doi.org/10.5194/acp-18-15471-2018

52. Shen, L., L.J. Mickley, and E. Gilleland, 2016: Impact of increasing heat waves on U.S. ozone episodes in the 2050s: Results from a multimodel analysis using extreme value theory. *Geophysical Research Letters*, **43** (8), 4017–4025. https://doi.org/10.1002/2016gl068432

53. Schnell, J.L., M.J. Prather, B. Josse, V. Naik, L.W. Horowitz, G. Zeng, D.T. Shindell, and G. Faluvegi, 2016: Effect of climate change on surface ozone over North America, Europe, and East Asia. *Geophysical Research Letters*, **43** (7), 3509–3518. https://doi.org/10.1002/2016gl068060

54. Westervelt, D.M., L.W. Horowitz, V. Naik, A.P.K. Tai, A.M. Fiore, and D.L. Mauzerall, 2016: Quantifying $PM_{2.5}$-meteorology sensitivities in a global climate model. *Atmospheric Environment*, **142**, 43–56. https://doi.org/10.1016/j.atmosenv.2016.07.040

55. Baasandorj, M., S.W. Hoch, R. Bares, J.C. Lin, S.S. Brown, D.B. Millet, R. Martin, K. Kelly, K.J. Zarzana, C.D. Whiteman, W.P. Dube, G. Tonnesen, I.C. Jaramillo, and J. Sohl, 2017: Coupling between chemical and meteorological processes under persistent cold-air pool conditions: Evolution of wintertime $PM_{2.5}$ pollution events and $N_2O_5$ observations in Utah's Salt Lake Valley. *Environmental Science & Technology*, **51** (11), 5941–5950. https://doi.org/10.1021/acs.est.6b06603

56. Carling, G.T., D.P. Fernandez, K.A. Rey, C.A. Hale, M.M. Goodman, and S.T. Nelson, 2020: Using strontium isotopes to trace dust from a drying Great Salt Lake to adjacent urban areas and mountain snowpack. *Environmental Research Letters*, **15** (11), 114035. https://doi.org/10.1088/1748-9326/abbfc4

57. Jones, B.A. and J. Fleck, 2020: Shrinking lakes, air pollution, and human health: Evidence from California's Salton Sea. *Science of The Total Environment*, **712**, 136490. https://doi.org/10.1016/j.scitotenv.2019.136490

58. Wurtsbaugh, W.A., C. Miller, S.E. Null, R.J. DeRose, P. Wilcock, M. Hahnenberger, F. Howe, and J. Moore, 2017: Decline of the world's saline lakes. *Nature Geoscience*, **10** (11), 816–821. https://doi.org/10.1038/ngeo3052

59. Duffy, P.B., C.B. Field, N.S. Diffenbaugh, S.C. Doney, Z. Dutton, S. Goodman, L. Heinzerling, S. Hsiang, D.B. Lobell, L.J. Mickley, S. Myers, S.M. Natali, C. Parmesan, S. Tierney, and A.P. Williams, 2019: Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases. *Science*, **363** (6427), 5982. https://doi.org/10.1126/science.aat5982

60. Hall, D.K., D.S. O'Leary, N.E. DiGirolamo, W. Miller, and D.H. Kang, 2021: The role of declining snow cover in the desiccation of the Great Salt Lake, Utah, using MODIS data. *Remote Sensing of Environment*, **252**, 112106. https://doi.org/10.1016/j.rse.2020.112106

61. Wang, J., C. Song, J.T. Reager, F. Yao, J.S. Famiglietti, Y. Sheng, G.M. MacDonald, F. Brun, H.M. Schmied, R.A. Marston, and Y. Wada, 2018: Recent global decline in endorheic basin water storages. *Nature Geoscience*, **11** (12), 926–932. https://doi.org/10.1038/s41561-018-0265-7

62. Achakulwisut, P., S.C. Anenberg, J.E. Neumann, S.L. Penn, N. Weiss, A. Crimmins, N. Fann, J. Martinich, H. Roman, and L.J. Mickley, 2019: Effects of increasing aridity on ambient dust and public health in the U.S. Southwest under climate change. *GeoHealth*, **3** (5), 127–144. https://doi.org/10.1029/2019gh000187

63. Li, Y., L.J. Mickley, and J.O. Kaplan, 2021: Response of dust emissions in southwestern North America to 21st century trends in climate, $CO_2$ fertilization, and land use: Implications for air quality. *Atmospheric Chemistry and Physics*, **21** (1), 57–68. https://doi.org/10.5194/acp-21-57-2021

64. Fiore, A.M., V. Naik, and E.M. Leibensperger, 2015: Air quality and climate connections. *Journal of the Air & Waste Management Association*, **65** (6), 645–685. https://doi.org/10.1080/10962247.2015.1040526

65. The Royal Society, 2021: Effects of Net-Zero Policies and Climate Change on Air Quality. The Royal Society, London, UK, 106 pp. https://royalsociety.org/topics-policy/projects/air-quality-climate-change/

66. Wu, S., L.J. Mickley, E.M. Leibensperger, D.J. Jacob, D. Rind, and D.G. Streets, 2008: Effects of 2000–2050 global change on ozone air quality in the United States. *Journal of Geophysical Research: Atmospheres*, **113** (D6). https://doi.org/10.1029/2007jd008917

67. Nolte, C.G., T.L. Spero, J.H. Bowden, M.C. Sarofim, J. Martinich, and M.S. Mallard, 2021: Regional temperature-ozone relationships across the U.S. under multiple climate and emissions scenarios. *Journal of the Air & Waste Management Association*, **71** (10), 1251–1264. https://doi.org/10.1080/10962247.2021.1970048

68. Zanis, P., D. Akritidis, S. Turnock, V. Naik, S. Szopa, A.K. Georgoulias, S.E. Bauer, M. Deushi, L.W. Horowitz, J. Keeble, P. Le Sager, F.M. O'Connor, N. Oshima, K. Tsigaridis, and T. van Noije, 2022: Climate change penalty and benefit on surface ozone: A global perspective based on CMIP6 earth system models. *Environmental Research Letters*, **17** (2), 024014. https://doi.org/10.1088/1748-9326/ac4a34

69. Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (42), 11770–11775. https://doi.org/10.1073/pnas.1607171113

70. Abatzoglou, J.T., D.S. Battisti, A.P. Williams, W.D. Hansen, B.J. Harvey, and C.A. Kolden, 2021: Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth & Environment*, **2** (1), 227. https://doi.org/10.1038/s43247-021-00299-0

71. Ford, B., M. Val Martin, S.E. Zelasky, E.V. Fischer, S.C. Anenberg, C.L. Heald, and J.R. Pierce, 2018: Future fire impacts on smoke concentrations, visibility, and health in the contiguous United States. *GeoHealth*, **2** (8), 229–247. https://doi.org/10.1029/2018gh000144

72. Liu, Y., Y. Liu, J. Fu, C.-E. Yang, X. Dong, H. Tian, B. Tao, J. Yang, Y. Wang, Y. Zou, and Z. Ke, 2022: Projection of future wildfire emissions in western USA under climate change: Contributions from changes in wildfire, fuel loading and fuel moisture. *International Journal of Wildland Fire*, **31** (1), 1–13. https://doi.org/10.1071/wf20190

73. Stambaugh, M.C., R.P. Guyette, E.D. Stroh, M.A. Struckhoff, and J.B. Whittier, 2018: Future southcentral US wildfire probability due to climate change. *Climatic Change*, **147** (3–4), 617–631. https://doi.org/10.1007/s10584-018-2156-8

74. Jaffe, D.A., S.M. O'Neill, N.K. Larkin, A.L. Holder, D.L. Peterson, J.E. Halofsky, and A.G. Rappold, 2020: Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air & Waste Management Association*, **70** (6), 583–615. https://doi.org/10.1080/10962247.2020.1749731

75. Juliano, T.W., P.A. Jiménez, B. Kosović, T. Eidhammer, G. Thompson, L.K. Berg, J. Fast, A. Motley, and A. Polidori, 2022: Smoke from 2020 United States wildfires responsible for substantial solar energy forecast errors. *Environmental Research Letters*, **17** (3), 034010. https://doi.org/10.1088/1748-9326/ac5143

76. Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara, 2021: The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2011048118. https://doi.org/10.1073/pnas.2011048118

77. O'Dell, K., R.S. Hornbrook, W. Permar, E.J.T. Levin, L.A. Garofalo, E.C. Apel, N.J. Blake, A. Jarnot, M.A. Pothier, D.K. Farmer, L. Hu, T. Campos, B. Ford, J.R. Pierce, and E.V. Fischer, 2020: Hazardous air pollutants in fresh and aged western US wildfire smoke and implications for long-term exposure. *Environmental Science & Technology*, **54** (19), 11838–11847. https://doi.org/10.1021/acs.est.0c04497

78. Xie, Y., M. Lin, B. Decharme, C. Delire, L.W. Horowitz, D.M. Lawrence, F. Li, and R. Séférian, 2022: Tripling of western US particulate pollution from wildfires in a warming climate. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (14), e2111372119. https://doi.org/10.1073/pnas.2111372119

79. McClure, C.D. and D.A. Jaffe, 2018: US particulate matter air quality improves except in wildfire-prone areas. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (31), 7901–7906. https://doi.org/10.1073/pnas.1804353115

80. Brey, S.J. and E.V. Fischer, 2016: Smoke in the city: How often and where does smoke impact summertime ozone in the United States? *Environmental Science & Technology*, **50** (3), 1288–1294. https://doi.org/10.1021/acs.est.5b05218

81. Buysse, C.E., A. Kaulfus, U. Nair, and D.A. Jaffe, 2019: Relationships between particulate matter, ozone, and nitrogen oxides during urban smoke events in the western US. *Environmental Science & Technology*, **53** (21), 12519–12528. https://doi.org/10.1021/acs.est.9b05241

82. Hodshire, A.L., A. Akherati, M.J. Alvarado, B. Brown-Steiner, S.H. Jathar, J.L. Jimenez, S.M. Kreidenweis, C.R. Lonsdale, T.B. Onasch, A.M. Ortega, and J.R. Pierce, 2019: Aging effects on biomass burning aerosol mass and composition: A critical review of field and laboratory studies. *Environmental Science & Technology*, **53** (17), 10007–10022. https://doi.org/10.1021/acs.est.9b02588

83. Boaggio, K., S.D. LeDuc, R.B. Rice, P.F. Duffney, K.M. Foley, A.L. Holder, S. McDow, and C.P. Weaver, 2022: Beyond particulate matter mass: Heightened levels of lead and other pollutants associated with destructive fire events in California. *Environmental Science & Technology*, **56** (20), 14272–14283. https://doi.org/10.1021/acs.est.2c02099

84. CARB, 2021: Camp Fire Air Quality Data Analysis. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/2021-07/Camp_Fire_report_July2021.pdf

85. Hauser, N., K.C. Conlon, A. Desai, and L.N. Kobziar, 2021: Climate change and infections on the move in North America. *Infection and Drug Resistance*, **14**, 5711–5723. https://doi.org/10.2147/idr.s305077

86. Kobziar, L.N., M.R.A. Pingree, H. Larson, T.J. Dreaden, S. Green, and J.A. Smith, 2018: Pyroaerobiology: The aerosolization and transport of viable microbial life by wildland fire. *Ecosphere*, **9** (11), e02507. https://doi.org/10.1002/ecs2.2507

87. Kobziar, L.N., D. Vuono, R. Moore, B.C. Christner, T. Dean, D. Betancourt, A.C. Watts, J. Aurell, and B. Gullett, 2022: Wildland fire smoke alters the composition, diversity, and potential atmospheric function of microbial life in the aerobiome. *ISME Communications*, **2** (1), 8. https://doi.org/10.1038/s43705-022-00089-5

88. Abdo, M., I. Ward, K. O'Dell, B. Ford, J.R. Pierce, E.V. Fischer, and J.L. Crooks, 2019: Impact of wildfire smoke on adverse pregnancy outcomes in Colorado, 2007–2015. *International Journal of Environmental Research and Public Health*, **16** (19), 3720. https://doi.org/10.3390/ijerph16193720

89. Chen, G., Y. Guo, X. Yue, S. Tong, A. Gasparrini, M.L. Bell, B. Armstrong, J. Schwartz, J.J.K. Jaakkola, A. Zanobetti, E. Lavigne, P.H. Nascimento Saldiva, H. Kan, D. Royé, A. Milojevic, A. Overcenco, A. Urban, A. Schneider, A. Entezari, A.M. Vicedo-Cabrera, A. Zeka, A. Tobias, B. Nunes, B. Alahmad, B. Forsberg, S.-C. Pan, C. Íñiguez, C. Ameling, C. De la Cruz Valencia, C. Åström, D. Houthuijs, D. Van Dung, E. Samoli, F. Mayvaneh, F. Sera, G. Carrasco-Escobar, Y. Lei, H. Orru, H. Kim, I.-H. Holobaca, J. Kyselý, J.P. Teixeira, J. Madureira, K. Katsouyanni, M. Hurtado-Díaz, M. Maasikmets, M.S. Ragettli, M. Hashizume, M. Stafoggia, M. Pascal, M. Scortichini, M. de Sousa Zanotti Stagliorio Coêlho, N. Valdés Ortega, N.R.I. Ryti, N. Scovronick, P. Matus, P. Goodman, R.M. Garland, R. Abrutzky, S.O. Garcia, S. Rao, S. Fratianni, T.N. Dang, V. Colistro, V. Huber, W. Lee, X. Seposo, Y. Honda, Y.L. Guo, T. Ye, W. Yu, M.J. Abramson, J.M. Samet, and S. Li, 2021: Mortality risk attributable to wildfire-related $PM_{2.5}$ pollution: A global time series study in 749 locations. *The Lancet Planetary Health*, **5** (9), e579–e587. https://doi.org/10.1016/s2542-5196(21)00200-x

90. Dodd, W., P. Scott, C. Howard, C. Scott, C. Rose, A. Cunsolo, and J. Orbinski, 2018: Lived experience of a record wildfire season in the Northwest Territories, Canada. *Canadian Journal of Public Health*, **109** (3), 327–337. https://doi.org/10.17269/s41997-018-0070-5

91. Doubleday, A., J. Schulte, L. Sheppard, M. Kadlec, R. Dhammapala, J. Fox, and T. Busch Isaksen, 2020: Mortality associated with wildfire smoke exposure in Washington state, 2006–2017: A case-crossover study. *Environmental Health*, **19** (1), 4. https://doi.org/10.1186/s12940-020-0559-2

92. Liu, J.C., G. Pereira, S.A. Uhl, M.A. Bravo, and M.L. Bell, 2015: A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. *Environmental Research*, **136**, 120–132. https://doi.org/10.1016/j.envres.2014.10.015

93. Reid, C.E., M. Brauer, F.H. Johnston, M. Jerrett, J.R. Balmes, and C.T. Elliott, 2016: Critical review of health impacts of wildfire smoke exposure. *Environmental Health Perspectives*, **124** (9), 1334–1343. https://doi.org/10.1289/ehp.1409277

94. Schwarz, L., A. Dimitrova, R. Aguilera, R. Basu, A. Gershunov, and T. Benmarhnia, 2022: Smoke and COVID-19 case fatality ratios during California wildfires. *Environmental Research Letters*, **17** (1), 014054. https://doi.org/10.1088/1748-9326/ac4538

95. Zhou, X., K. Josey, L. Kamareddine, M.C. Caine, T. Liu, L.J. Mickley, M. Cooper, and F. Dominici, 2021: Excess of COVID-19 cases and deaths due to fine particulate matter exposure during the 2020 wildfires in the United States. *Science Advances*, **7** (33), 8789. https://doi.org/10.1126/sciadv.abi8789

96. Fann, N., B. Alman, R.A. Broome, G.G. Morgan, F.H. Johnston, G. Pouliot, and A.G. Rappold, 2018: The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012. *Science of The Total Environment*, **610–611**, 802–809. https://doi.org/10.1016/j.scitotenv.2017.08.024

97. O'Dell, K., K. Bilsback, B. Ford, S.E. Martenies, S. Magzamen, E.V. Fischer, and J.R. Pierce, 2021: Estimated mortality and morbidity attributable to smoke plumes in the United States: Not just a western US problem. *GeoHealth*, **5** (9), e2021GH000457. https://doi.org/10.1029/2021gh000457

98. Liu, J.C., A. Wilson, L.J. Mickley, K. Ebisu, M.P. Sulprizio, Y. Wang, R.D. Peng, X. Yue, F. Dominici, and M.L. Bell, 2017: Who among the elderly is most vulnerable to exposure to and health risks of fine particulate matter from wildfire smoke? *American Journal of Epidemiology*, **186** (6), 730–735. https://doi.org/10.1093/aje/kwx141

99. Navarro, K.M., M.T. Kleinman, C.E. Mackay, T.E. Reinhardt, J.R. Balmes, G.A. Broyles, R.D. Ottmar, L.P. Naher, and J.W. Domitrovich, 2019: Wildland firefighter smoke exposure and risk of lung cancer and cardiovascular disease mortality. *Environmental Research*, **173**, 462–468. https://doi.org/10.1016/j.envres.2019.03.060

100. Woo, S.H.L., J.C. Liu, X. Yue, L.J. Mickley, and M.L. Bell, 2020: Air pollution from wildfires and human health vulnerability in Alaskan communities under climate change. *Environmental Research Letters*, **15** (9), 094019. https://doi.org/10.1088/1748-9326/ab9270

101. Liu, J.C., L.J. Mickley, M.P. Sulprizio, X. Yue, R.D. Peng, F. Dominici, and M.L. Bell, 2016: Future respiratory hospital admissions from wildfire smoke under climate change in the Western US. *Environmental Research Letters*, **11** (12), 124018. https://doi.org/10.1088/1748-9326/11/12/124018

102. Stevens, J.T., B.M. Collins, J.W. Long, M.P. North, S.J. Prichard, L.W. Tarnay, and A.M. White, 2016: Evaluating potential trade-offs among fuel treatment strategies in mixed-conifer forests of the Sierra Nevada. *Ecosphere*, **7** (9), e01445. https://doi.org/10.1002/ecs2.1445

103. Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Povak, and F.K. Lake, 2021: Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*, **31** (8), e02432. https://doi.org/10.1002/eap.2432

104. USFS, 2022: Confronting the Wildlife Crisis: A Strategy for Protecting Communities and Improving Resilience in America's Forests. FS-1187a. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/sites/default/files/Confronting-Wildfire-Crisis.pdf

105. Larson, E.R., K.F. Kipfmueller, and L.B. Johnson, 2021: People, fire, and pine: Linking human agency and landscape in the Boundary Waters Canoe Area Wilderness and beyond. *Annals of the American Association of Geographers*, **111** (1), 1–25. https://doi.org/10.1080/24694452.2020.1768042

106. Long, J.W., F.K. Lake, and R.W. Goode, 2021: The importance of Indigenous cultural burning in forested regions of the Pacific West, USA. *Forest Ecology and Management*, **500**, 119597. https://doi.org/10.1016/j.foreco.2021.119597

107. Larkin, N.K., S.M. Raffuse, S. Huang, N. Pavlovic, P. Lahm, and V. Rao, 2020: The comprehensive fire information reconciled emissions (CFIRE) inventory: Wildland fire emissions developed for the 2011 and 2014 U.S. national emissions inventory. *Journal of the Air & Waste Management Association*, **70** (11), 1165–1185. https://doi.org/10.1080/10962247.2020.1802365

108. Afrin, S. and F. Garcia-Menendez, 2021: Potential impacts of prescribed fire smoke on public health and socially vulnerable populations in a southeastern U.S. state. *Science of The Total Environment*, **794**, 148712. https://doi.org/10.1016/j.scitotenv.2021.148712

109. NWCG, 2020: NWCG Smoke Management Guide for Prescribed Fire. PMS 420-3, NFES 001279, Peterson, J., P. Lahm, M. Fitch, M. George, D. Haddow, M. Melvin, J. Hyde, and E. Eberhardt, Eds. National Wildfire Coordinating Group. https://www.nwcg.gov/sites/default/files/publications/pms420-3.pdf

110. EPA, 2021: Comparative Assessment of the Impacts of Prescribed Fire Versus Wildfire (CAIF): A Case Study in the Western U.S. EPA/600/R-21/197. U.S. Environmental Protection Agency, Washington, DC. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=352824

111. Hill, L.A., J. Jaeger, and A. Smith, 2022: Can Prescribed Fires Mitigate Health Harm? A Review of Air Quality and Public Health Implications of Wildfire and Prescribed Fire. Amercan Lung Association and PSE Healthy Energy. https://www.lung.org/getmedia/fd7ff728-56d9-4b33-82eb-abd06f01bc3b/pse_wildfire-and-prescribed-fire-brief_final.pdf

112. Chen, J., K. Anderson, R. Pavlovic, M.D. Moran, P. Englefield, D.K. Thompson, R. Munoz-Alpizar, and H. Landry, 2019: The FireWork v2.0 air quality forecast system with biomass burning emissions from the Canadian Forest Fire Emissions Prediction System v2.03. *Geoscientific Model Development*, **12** (7), 3283–3310. https://doi.org/10.5194/gmd-12-3283-2019

113. June, N., J. Vaughan, Y. Lee, and B.K. Lamb, 2021: Operational bias correction for $PM_{2.5}$ using the AIRPACT air quality forecast system in the Pacific Northwest. *Journal of the Air & Waste Management Association*, **71** (4), 515–527. https://doi.org/10.1080/10962247.2020.1856216

114. Lee, P., J. McQueen, I. Stajner, J. Huang, L. Pan, D. Tong, H. Kim, Y. Tang, S. Kondragunta, M. Ruminski, S. Lu, E. Rogers, R. Saylor, P. Shafran, H.-C. Huang, J. Gorline, S. Upadhayay, and R. Artz, 2017: NAQFC developmental forecast guidance for fine particulate matter ($PM_{2.5}$). *Weather and Forecasting*, **32** (1), 343–360. https://doi.org/10.1175/waf-d-15-0163.1

115. O'Neill, S., P. Xian, J. Flemming, M. Cope, A. Baklanov, N. Larkin, J. Vaughan, D. Tong, R. Howard, R. Stull, D. Davignon, R. Ahmadov, M. Odman, J. Innis, M. Azzi, C. Gan, R. Pavlovic, B.N. Chew, J. Reid, and A. MacNeil, 2022: Profiles of Operational and Research Forecasting of Smoke and Air Quality Around the World. ESS Open Archive. https://doi.org/10.1002/essoar.10512975.1

116. Xian, P., J.S. Reid, E.J. Hyer, C.R. Sampson, J.I. Rubin, M. Ades, N. Asencio, S. Basart, A. Benedetti, P.S. Bhattacharjee, M.E. Brooks, P.R. Colarco, A.M. da Silva, T.F. Eck, J. Guth, O. Jorba, R. Kouznetsov, Z. Kipling, M. Sofiev, C. Perez Garcia-Pando, Y. Pradhan, T. Tanaka, J. Wang, D.L. Westphal, K. Yumimoto, and J. Zhang, 2019: Current state of the global operational aerosol multi-model ensemble: An update from the International Cooperative for Aerosol Prediction (ICAP). *Quarterly Journal of the Royal Meteorological Society*, **145** (S1), 176–209. https://doi.org/10.1002/qj.3497

117. EPA, 2021: Wildfire Smoke: A Guide for Public Health Officials. EPA-452/R-21-901. U.S. Environmental Protection Agency. https://www.airnow.gov/sites/default/files/2021-09/wildfire-smoke-guide_0.pdf

118. Barn, P.K., C.T. Elliott, R.W. Allen, T. Kosatsky, K. Rideout, and S.B. Henderson, 2016: Portable air cleaners should be at the forefront of the public health response to landscape fire smoke. *Environmental Health*, **15** (1), 116. https://doi.org/10.1186/s12940-016-0198-9

119. Davison, G., K.K. Barkjohn, G.S.W. Hagler, A.L. Holder, S. Coefield, C. Noonan, and B. Hassett-Sipple, 2021: Creating clean air spaces during wildland fire smoke episodes: Web Summit summary. *Frontiers in Public Health*, **9**, 508971. https://doi.org/10.3389/fpubh.2021.508971

120. Fisk, W.J. and W.R. Chan, 2017: Health benefits and costs of filtration interventions that reduce indoor exposure to $PM_{2.5}$ during wildfires. *Indoor Air*, **27** (1), 191–204. https://doi.org/10.1111/ina.12285

121. Rappold, A.G., N.L. Fann, J. Crooks, J. Huang, W.E. Cascio, R.B. Devlin, and D. Diaz-Sanchez, 2014: Forecast-based interventions can reduce the health and economic burden of wildfires. *Environmental Science & Technology*, **48** (18), 10571–10579. https://doi.org/10.1021/es5012725

122. Lahm, P. and N.K. Larkin, 2020: The interagency wildland fire air quality response program. *The Magazine for Environmental Managers*, **24**, 9–15.

123. John D. Dingell Jr. Conservation, Management, and Recreation Act. 116th Congress, Pub. L. No. 116–119, 133 Stat. 580–839, March 12, 2019. https://www.congress.gov/bill/116th-congress/senate-bill/47/text

124. Rappold, A.G., M.C. Hano, S. Prince, L. Wei, S.M. Huang, C. Baghdikian, B. Stearns, X. Gao, S. Hoshiko, W.E. Cascio, D. Diaz-Sanchez, and B. Hubbell, 2019: Smoke sense initiative leverages citizen science to address the growing wildfire-related public health problem. *GeoHealth*, **3** (12), 443–457. https://doi.org/10.1029/2019gh000199

125. Burke, M., S. Heft-Neal, J. Li, A. Driscoll, P. Baylis, M. Stigler, J.A. Weill, J.A. Burney, J. Wen, M.L. Childs, and C.F. Gould, 2022: Exposures and behavioural responses to wildfire smoke. *Nature Human Behaviour*, **6** (10), 1351–1361. https://doi.org/10.1038/s41562-022-01396-6

126. Rice, M.B., S.B. Henderson, A.A. Lambert, K.R. Cromar, J.A. Hall, W.E. Cascio, P.G. Smith, B.J. Marsh, S. Coefield, J.R. Balmes, A. Kamal, M.I. Gilmour, C. Carlsten, K.M. Navarro, G.W. Collman, A. Rappold, M.D. Miller, S.L. Stone, and D.L. Costa, 2021: Respiratory impacts of wildland fire smoke: Future challenges and policy opportunities. An official American Thoracic Society workshop report. *Annals of the American Thoracic Society*, **18** (6), 921–930. https://doi.org/10.1513/annalsats.202102-148st

127. EPA, 2022: AirNow Fire and Smoke Map. U.S. Environmental Protection Agency. https://fire.airnow.gov/

128. Bullard, R.D., P. Mohai, R. Saha, and B. Wright, 2008: Toxic wastes and race at twenty: Why race still matters after all of these years. *Environmental Law*, **38** (2), 371–411. http://www.jstor.org/stable/43267204

129. Di, Q., Y. Wang, A. Zanobetti, Y. Wang, P. Koutrakis, C. Choirat, F. Dominici, and J.D. Schwartz, 2017: Air pollution and mortality in the Medicare population. *New England Journal of Medicine*, **376** (26), 2513–2522. https://doi.org/10.1056/nejmoa1702747

130. Hajat, A., C. Hsia, and M.S. O'Neill, 2015: Socioeconomic disparities and air pollution exposure: A global review. *Current Environmental Health Reports*, **2** (4), 440–450. https://doi.org/10.1007/s40572-015-0069-5

131. Wilson, S.M., H. Fraser-Rahim, E. Williams, H. Zhang, L. Rice, E. Svendsen, and W. Abara, 2012: Assessment of the distribution of toxic release inventory facilities in metropolitan Charleston: An environmental justice case study. *American Journal of Public Health*, **102** (10), 1974–1980. https://doi.org/10.2105/ajph.2012.300700

132. Ard, K., 2015: Trends in exposure to industrial air toxins for different racial and socioeconomic groups: A spatial and temporal examination of environmental inequality in the U.S. from 1995 to 2004. *Social Science Research*, **53**, 375–390. https://doi.org/10.1016/j.ssresearch.2015.06.019

133. Castillo, M.D., P.L. Kinney, V. Southerland, C.A. Arno, K. Crawford, A. van Donkelaar, M. Hammer, R.V. Martin, and S.C. Anenberg, 2021: Estimating intra-urban inequities in $PM_{2.5}$-attributable health impacts: A case study for Washington, DC. *GeoHealth*, **5** (11), e2021GH000431. https://doi.org/10.1029/2021gh000431

134. Clark, L.P., D.B. Millet, and J.D. Marshall, 2017: Changes in transportation-related air pollution exposures by race-ethnicity and socioeconomic status: Outdoor nitrogen dioxide in the United States in 2000 and 2010. *Environmental Health Perspectives*, **125** (9), 097012. https://doi.org/10.1289/ehp959

135. Colmer, J., I. Hardman, J. Shimshack, and J. Voorheis, 2020: Disparities in $PM_{2.5}$ air pollution in the United States. *Science*, **369** (6503), 575–578. https://doi.org/10.1126/science.aaz9353

136. Kravitz-Wirtz, N., K. Crowder, A. Hajat, and V. Sass, 2016: The long-term dynamics of racial/ethnic inequality in neighborhood air pollution exposure, 1990–2009. *Du Bois Review: Social Science Research on Race*, **13** (2), 237–259. https://doi.org/10.1017/s1742058x16000205

137. Liu, J., L.P. Clark, M.J. Bechle, A. Hajat, S.Y. Kim, A.L. Robinson, L. Sheppard, A.A. Szpiro, and J.D. Marshall, 2021: Disparities in air pollution exposure in the United States by race/ethnicity and income, 1990–2010. *Environmental Health Perspectives*, **129** (12), 127005. https://doi.org/10.1289/ehp8584

138. Demetillo, M.A.G., C. Harkins, B.C. McDonald, P.S. Chodrow, K. Sun, and S.E. Pusede, 2021: Space-based observational constraints on $NO_2$ air pollution inequality from diesel traffic in major US cities. *Geophysical Research Letters*, **48** (17), e2021GL094333. https://doi.org/10.1029/2021gl094333

139. Tessum, C.W., J.S. Apte, A.L. Goodkind, N.Z. Muller, K.A. Mullins, D.A. Paolella, S. Polasky, N.P. Springer, S.K. Thakrar, J.D. Marshall, and J.D. Hill, 2019: Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6001–6006. https://doi.org/10.1073/pnas.1818859116

140. Johnson Gaither, C., S. Afrin, F. Garcia-Menendez, M.T. Odman, R. Huang, S. Goodrick, and A. Ricardo da Silva, 2019: African American exposure to prescribed fire smoke in Georgia, USA. *International Journal of Environmental Research and Public Health*, **16** (17), 3079. https://doi.org/10.3390/ijerph16173079

141. Mirabelli, M.C., S. Wing, S.W. Marshall, and T.C. Wilcosky, 2006: Race, poverty, and potential exposure of middle-school students to air emissions from confined swine feeding operations. *Environmental Health Perspectives*, **114** (4), 591–596. https://doi.org/10.1289/ehp.8586

142. Ogneva-Himmelberger, Y., L. Huang, and H. Xin, 2015: CALPUFF and CAFOs: Air pollution modeling and environmental justice analysis in the North Carolina hog industry. *ISPRS International Journal of Geo-Information*, **4** (1), 150–171. https://doi.org/10.3390/ijgi4010150

143. Son, J.-Y., M.L. Miranda, and M.L. Bell, 2021: Exposure to concentrated animal feeding operations (CAFOs) and risk of mortality in North Carolina, USA. *Science of The Total Environment*, **799**, 149407. https://doi.org/10.1016/j.scitotenv.2021.149407

144. Wing, S., D. Cole, and G. Grant, 2000: Environmental injustice in North Carolina's hog industry. *Environmental Health Perspectives*, **108** (3), 225–231. https://doi.org/10.1289/ehp.00108225

145. Wing, S. and S. Wolf, 2000: Intensive livestock operations, health, and quality of life among eastern North Carolina residents. *Environmental Health Perspectives*, **108** (3), 233–238. https://doi.org/10.1289/ehp.00108233

146. Thind, M.P.S., C.W. Tessum, I.L. Azevedo, and J.D. Marshall, 2019: Fine particulate air pollution from electricity generation in the US: Health impacts by race, income, and geography. *Environmental Science & Technology*, **53** (23), 14010–14019. https://doi.org/10.1021/acs.est.9b02527

147. Emanuel, R.E., M.A. Caretta, L. Rivers III, and P. Vasudevan, 2021: Natural gas gathering and transmission pipelines and social vulnerability in the United States. *GeoHealth*, **5** (6), e2021GH000442. https://doi.org/10.1029/2021gh000442

148. González, D.J.X., C.M. Morton, L.A.L. Hill, D.R. Michanowicz, R.J. Rossi, S.B.C. Shonkoff, J.A. Casey, and R. Morello-Frosch, 2023: Temporal trends of racial and socioeconomic disparities in population exposures to upstream oil and gas development in California. *GeoHealth*, **7** (3), e2022GH000690. https://doi.org/10.1029/2022gh000690

149. Bryant, B. and P. Mohai, 2019: *Race And The Incidence Of Environmental Hazards: A Time For Discourse*, 1st ed. Routledge, New York, 251 pp. https://doi.org/10.4324/9780429303661

150. Lane, H.M., R. Morello-Frosch, J.D. Marshall, and J.S. Apte, 2022: Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environmental Science & Technology Letters*, **9** (4), 345–350. https://doi.org/10.1021/acs.estlett.1c01012

151. Morello-Frosch, R. and R. Lopez, 2006: The riskscape and the color line: Examining the role of segregation in environmental health disparities. *Environmental Research*, **102** (2), 181–196. https://doi.org/10.1016/j.envres.2006.05.007

152. Wilson, S.M., 2009: An ecologic framework to study and address environmental justice and community health issues. *Environmental Justice*, **2** (1), 15–24. https://doi.org/10.1089/env.2008.0515

153. Bell, M.L., A. Zanobetti, and F. Dominici, 2013: Evidence on vulnerability and susceptibility to health risks associated with short-term exposure to particulate matter: A systematic review and meta-analysis. *American Journal of Epidemiology*, **178** (6), 865–876. https://doi.org/10.1093/aje/kwt090

154. Josey, K.P., S.W. Delaney, X. Wu, R.C. Nethery, P. DeSouza, D. Braun, and F. Dominici, 2023: Air pollution and mortality at the intersection of race and social class. *New England Journal of Medicine*, **388** (15), 1396–1404. https://doi.org/10.1056/nejmsa2300523

155. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

156. Morello-Frosch, R. and O.K. Obasogie, 2023: The climate gap and the color line—Racial health inequities and climate change. *New England Journal of Medicine*, **388** (10), 943–949. https://doi.org/10.1056/nejmsb2213250

157. Anenberg, S.C., S. Haines, E. Wang, N. Nassikas, and P.L. Kinney, 2020: Synergistic health effects of air pollution, temperature, and pollen exposure: A systematic review of epidemiological evidence. *Environmental Health*, **19** (1), 130. https://doi.org/10.1186/s12940-020-00681-z

158. Lee, W., H.M. Choi, D. Kim, Y. Honda, Y.-L. Leon Guo, and H. Kim, 2019: Synergic effect between high temperature and air pollution on mortality in Northeast Asia. *Environmental Research*, **178**, 108735. https://doi.org/10.1016/j.envres.2019.108735

159. McDonald, R.I., T. Biswas, C. Sachar, I. Housman, T.M. Boucher, D. Balk, D. Nowak, E. Spotswood, C.K. Stanley, and S. Leyk, 2021: The tree cover and temperature disparity in US urbanized areas: Quantifying the association with income across 5,723 communities. *PLoS ONE*, **16** (4), e0249715. https://doi.org/10.1371/journal.pone.0249715

160. O'Neill, M.S., A. Zanobetti, and J. Schwartz, 2005: Disparities by race in heat-related mortality in four US cities: The role of air conditioning prevalence. *Journal of Urban Health*, **82** (2), 191–197. https://doi.org/10.1093/jurban/jti043

161. Romitti, Y., I. Sue Wing, K.R. Spangler, and G.A. Wellenius, 2022: Inequality in the availability of residential air conditioning across 115 US metropolitan areas. *PNAS Nexus*, **1** (4), 210. https://doi.org/10.1093/pnasnexus/pgac210

162. Shrestha, P.M., J.L. Humphrey, E.J. Carlton, J.L. Adgate, K.E. Barton, E.D. Root, and S.L. Miller, 2019: Impact of outdoor air pollution on indoor air quality in low-income homes during wildfire seasons. *International Journal of Environmental Research and Public Health*, **16** (19), 3535. https://doi.org/10.3390/ijerph16193535

163. Dressel, I.M., M.A.G. Demetillo, L.M. Judd, S.J. Janz, K.P. Fields, K. Sun, A.M. Fiore, B.C. McDonald, and S.E. Pusede, 2022: Daily satellite observations of nitrogen dioxide air pollution inequality in New York City, New York and Newark, New Jersey: Evaluation and application. *Environmental Science & Technology*, **56** (22), 15298–15311. https://doi.org/10.1021/acs.est.2c02828

164. Anenberg, S.C., D.K. Henze, V. Tinney, P.L. Kinney, W. Raich, N. Fann, C.S. Malley, H. Roman, L. Lamsal, B. Duncan, R.V. Martin, A. van Donkelaar, M. Brauer, R. Doherty, J.E. Jonson, Y. Davila, K. Sudo, and J.C.I. Kuylenstierna, 2018: Estimates of the global burden of ambient $PM_{2.5}$, ozone, and $NO_2$ on asthma incidence and emergency room visits. *Environmental Health Perspectives*, **126** (10), 107004. https://doi.org/10.1289/ehp3766

165. Wu, J., C. Ren, R.J. Delfino, J. Chung, M. Wilhelm, and B. Ritz, 2009: Association between local traffic-generated air pollution and preeclampsia and preterm delivery in the South Coast Air Basin of California. *Environmental Health Perspectives*, **117** (11), 1773–1779. https://doi.org/10.1289/ehp.0800334

166. Chan, N.W. and J.W. Morrow, 2019: Unintended consequences of cap-and-trade? Evidence from the Regional Greenhouse Gas Initiative. *Energy Economics*, **80**, 411–422. https://doi.org/10.1016/j.eneco.2019.01.007

167. Hernandez-Cortes, D. and K. Meng, 2020: Do Environmental Markets Cause Environmental Injustice? Evidence from California's Carbon Market. Working Paper 27205. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w27205

168. Cushing, L., D. Blaustein-Rejto, M. Wander, M. Pastor, J. Sadd, A. Zhu, and R. Morello-Frosch, 2018: Carbon trading, co-pollutants, and environmental equity: Evidence from California's cap-and-trade program (2011–2015). *PLoS Medicine*, **15** (7), e1002604. https://doi.org/10.1371/journal.pmed.1002604

169. Wang, Y., J.S. Apte, J.D. Hill, C.E. Ivey, R.F. Patterson, A.L. Robinson, C.W. Tessum, and J.D. Marshall, 2022: Location-specific strategies for eliminating US national racial-ethnic $PM_{2.5}$ exposure inequality. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (44), e2205548119. https://doi.org/10.1073/pnas.2205548119

170. Hsiang, S., P. Oliva, and R. Walker, 2019: The distribution of environmental damages. *Review of Environmental Economics and Policy*, **13** (1), 83–103. https://doi.org/10.1093/reep/rey024

171. Ku, A., D.M. Kammen, and S. Castellanos, 2021: A quantitative, equitable framework for urban transportation electrification: Oakland, California as a mobility model of climate justice. *Sustainable Cities and Society*, **74**, 103179. https://doi.org/10.1016/j.scs.2021.103179

172. Al-Fadhli, F.M., Y. Kimura, E.C. McDonald-Buller, and D.T. Allen, 2012: Impact of flare destruction efficiency and products of incomplete combustion on ozone formation in Houston, Texas. *Industrial & Engineering Chemistry Research*, **51** (39), 12663–12673. https://doi.org/10.1021/ie201400z

173. Johnson, G.S., S.C. Washington, D.W. King, and J.M. Gomez, 2014: Air quality and health issues along Houston's ship channel: An exploratory environmental justice analysis of a vulnerable community (Pleasantville). *Race, Gender & Class*, **21** (3/4), 273–303. http://www.jstor.org/stable/43496996

174. Olaguer, E.P., M.H. Erickson, A. Wijesinghe, and B.S. Neish, 2016: Source attribution and quantification of benzene event emissions in a Houston ship channel community based on real-time mobile monitoring of ambient air. *Journal of the Air & Waste Management Association*, **66** (2), 164–172. https://doi.org/10.1080/10962247.2015.1081652

175. Chakraborty, J., T.W. Collins, S.E. Grineski, M.C. Montgomery, and M. Hernandez, 2014: Comparing disproportionate exposure to acute and chronic pollution risks: A case study in Houston, Texas: Acute and chronic pollution risks in Houston. *Risk Analysis*, **34** (11), 2005–2020. https://doi.org/10.1111/risa.12224

176. Collins, T.W., S.E. Grineski, J. Chakraborty, M.C. Montgomery, and M. Hernandez, 2015: Downscaling environmental justice analysis: Determinants of household-level hazardous air pollutant exposure in Greater Houston. *Annals of the Association of American Geographers*, **105** (4), 684–703. https://doi.org/10.1080/00045608.2015.1050754

177. Demetillo, M.A.G., A. Navarro, K.K. Knowles, K.P. Fields, J.A. Geddes, C.R. Nowlan, S.J. Janz, L.M. Judd, J. Al-Saadi, K. Sun, B.C. McDonald, G.S. Diskin, and S.E. Pusede, 2020: Observing nitrogen dioxide air pollution inequality using high-spatial-resolution remote sensing measurements in Houston, Texas. *Environmental Science & Technology*, **54** (16), 9882–9895. https://doi.org/10.1021/acs.est.0c01864

178. Lam, Y., R. Sivasubramanian, M. Guerrero, J. Parras, and A. Parras, 2021: Toxic Air Pollution in the Houston Ship Channel: Disparities Show Urgent Need for Environmental Justice. Natural Resources Defense Council, 8 pp. https://www.nrdc.org/sites/default/files/air-pollution-houston-ship-channel-ib.pdf

179. Linder, S.H., D. Marko, and K. Sexton, 2008: Cumulative cancer risk from air pollution in Houston: Disparities in risk burden and social disadvantage. *Environmental Science & Technology*, **42** (12), 4312–4322. https://doi.org/10.1021/es072042u

180. Loustaunau, M.G. and J. Chakraborty, 2019: Vehicular air pollution in Houston, Texas: An intra-categorical analysis of environmental injustice. *International Journal of Environmental Research and Public Health*, **16** (16), 2968. https://doi.org/10.3390/ijerph16162968

181. Flores, A.B., T.W. Collins, S.E. Grineski, and J. Chakraborty, 2020: Disparities in health effects and access to health care among Houston area residents after Hurricane Harvey. *Public Health Reports*, **135** (4), 511–523. https://doi.org/10.1177/0033354920930133

182. Misuri, A., V. Casson Moreno, N. Quddus, and V. Cozzani, 2019: Lessons learnt from the impact of Hurricane Harvey on the chemical and process industry. *Reliability Engineering & System Safety*, **190**, 106521. https://doi.org/10.1016/j.ress.2019.106521

183. Thomas, K.A., J.R. Elliott, and S. Chavez, 2018: Community perceptions of industrial risks before and after a toxic flood: The case of Houston and Hurricane Harvey. *Sociological Spectrum*, **38** (6), 371–386. https://doi.org/10.1080/02732173.2018.1532367

184. Reed, S.D., T.A. Lee, and D.C. McCrory, 2004: The economic burden of allergic rhinitis. *PharmacoEconomics*, **22** (6), 345–361. https://doi.org/10.2165/00019053-200422060-00002

185. Choi, Y.-J., K.S. Lee, and J.-W. Oh, 2021: The impact of climate change on pollen season and allergic sensitization to pollens. *Immunology and Allergy Clinics of North America*, **41** (1), 97–109. https://doi.org/10.1016/j.iac.2020.09.004

186. Gilles, S., C. Blume, M. Wimmer, A. Damialis, L. Meulenbroek, M. Gökkaya, C. Bergougnan, S. Eisenbart, N. Sundell, M. Lindh, L.M. Andersson, Å. Dahl, A. Chaker, F. Kolek, S. Wagner, A.U. Neumann, C.A. Akdis, J. Garssen, J. Westin, B. Van't Land, D.E. Davies, and C. Traidl-Hoffmann, 2020: Pollen exposure weakens innate defense against respiratory viruses. *Allergy*, **75** (3), 576–587. https://doi.org/10.1111/all.14047

187. Seth, D. and L. Bielory, 2021: Allergenic pollen season variations in the past two decades under changing climate in the United States. *Immunology and Allergy Clinics of North America*, **41** (1), 17–31. https://doi.org/10.1016/j.iac.2020.09.006

188. Berger, M., M. Bastl, J. Bouchal, L. Dirr, and U. Berger, 2021: The influence of air pollution on pollen allergy sufferers. *Allergologie Select*, **5**, 345–348. https://doi.org/10.5414/alx02284e

189. Gleason, J.A., L. Bielory, and J.A. Fagliano, 2014: Associations between ozone, $PM_{2.5}$, and four pollen types on emergency department pediatric asthma events during the warm season in New Jersey: A case-crossover study. *Environmental Research*, **132**, 421–429. https://doi.org/10.1016/j.envres.2014.03.035

190. Ochkur, S., K. Iijima, J. Gibson, J. Miech, J. Molar, M. Fraser, E. Jacobsen, B. Wright, H. Kita, P. Herckes, and M. Rank, 2022: Ozone and nitrogen oxide enhance the immunogenicity of ragweed pollen. *Journal of Allergy and Clinical Immunology*, **149** (2), AB29. https://doi.org/10.1016/j.jaci.2021.12.130

191. Damialis, A., S. Gilles, M. Sofiev, V. Sofieva, F. Kolek, et al., 2021: Higher airborne pollen concentrations correlated with increased SARS-CoV-2 infection rates, as evidenced from 31 countries across the globe. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (12), e2019034118. https://doi.org/10.1073/pnas.2019034118

192. Idrose, N.S., C.J. Lodge, B. Erbas, J.A. Douglass, D.S. Bui, and S.C. Dharmage, 2022: A review of the respiratory health burden attributable to short-term exposure to pollen. *International Journal of Environmental Research and Public Health*, **19** (12), 7541. https://doi.org/10.3390/ijerph19127541

193. Dbouk, T. and D. Drikakis, 2021: On pollen and airborne virus transmission. *Physics of Fluids*, **33** (6), 063313. https://doi.org/10.1063/5.0055845

194. Anderegg, W.R.L., J.T. Abatzoglou, L.D.L. Anderegg, L. Bielory, P.L. Kinney, and L. Ziska, 2021: Anthropogenic climate change is worsening North American pollen seasons. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (7), e2013284118. https://doi.org/10.1073/pnas.2013284118

195. Choi, Y.J., H.R. Oh, J.W. Oh, K.R. Kim, M.J. Kim, B.J. Kim, and W.G. Baek, 2018: Chamber and field studies demonstrate differential Amb a 1 contents in common ragweed depending on $CO_2$ levels. *Allergy, Asthma & Immunology Research*, **10** (3), 278–282. https://doi.org/10.4168/aair.2018.10.3.278

196. Ziska, L.H. and K.L. Ebi, 2021: Ch. 7. Climate change, carbon dioxide, and public health: The plant biology perspective. In: *Global Climate Change and Human Health: From Science to Practice*, 2nd ed. Lemery, J., K. Knowlton, and C. Sorensen, Eds. Wiley. https://www.wiley.com/en-au/Global+Climate+Change+and+Human+Health:+From+Science+to+Practice,+2nd+Edition-p-9781119667957

197. Ziska, L.H., J. Yang, M.B. Tomecek, and P.J. Beggs, 2016: Cultivar-specific changes in peanut yield, biomass, and allergenicity in response to elevated atmospheric carbon dioxide concentration. *Crop Science*, **56** (5), 2766–2774. https://doi.org/10.2135/cropsci2015.12.0741

198. Manangan, A., C. Brown, S. Saha, J. Bell, J. Hess, C. Uejio, S. Fineman, and P. Schramm, 2021: Long-term pollen trends and associations between pollen phenology and seasonal climate in Atlanta, Georgia (1992–2018). *Annals of Allergy, Asthma & Immunology*, **127** (4), 471–480. https://doi.org/10.1016/j.anai.2021.07.012

199. Paudel, B., T. Chu, M. Chen, V. Sampath, M. Prunicki, and K.C. Nadeau, 2021: Increased duration of pollen and mold exposure are linked to climate change. *Scientific Reports*, **11** (1), 12816. https://doi.org/10.1038/s41598-021-92178-z

200. Zhang, Y., L. Bielory, Z. Mi, T. Cai, A. Robock, and P. Georgopoulos, 2015: Allergenic pollen season variations in the past two decades under changing climate in the United States. *Global change biology*, **21** (4), 1581–1589. https://doi.org/10.1111/gcb.12755

201. Ziska, L.H., L. Makra, S.K. Harry, N. Bruffaerts, M. Hendrickx, F. Coates, A. Saarto, M. Thibaudon, G. Oliver, A. Damialis, A. Charalampopoulos, D. Vokou, S. Heiđmarsson, E. Guđjohnsen, M. Bonini, J.-W. Oh, K. Sullivan, L. Ford, G.D. Brooks, D. Myszkowska, E. Severova, R. Gehrig, G.D. Ramón, P.J. Beggs, K. Knowlton, and A.R. Crimmins, 2019: Temperature-related changes in airborne allergenic pollen abundance and seasonality across the Northern Hemisphere: A retrospective data analysis. *The Lancet Planetary Health*, **3** (3), e124–e131. https://doi.org/10.1016/s2542-5196(19)30015-4

202. Ziska, L., K. Knowlton, C. Rogers, D. Dalan, N. Tierney, M.A. Elder, W. Filley, J. Shropshire, L.B. Ford, C. Hedberg, P. Fleetwood, K.T. Hovanky, T. Kavanaugh, G. Fulford, R.F. Vrtis, J.A. Patz, J. Portnoy, F. Coates, L. Bielory, and D. Frenz, 2011: Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *Proceedings of the National Academy of Sciences of the United States of America*, **108** (10), 4248–4251. https://doi.org/10.1073/pnas.1014107108

203. Damialis, A., C. Traidl-Hoffmann, and R. Treudler, 2019: Ch. 3. Climate change and pollen allergies. In: *Biodiversity and Health in the Face of Climate Change*. Marselle, M.R., J. Stadler, H. Korn, K.N. Irvine, and A. Bonn, Eds. Springer, Cham, Switzerland, 47–66. https://doi.org/10.1007/978-3-030-02318-8_3

204. Cai, T. 2019: Modeling Impacts of Climate Change on Air Quality and Associated Human Exposures. Doctor of Philosophy in Environmental Sciences, Rutgers, The State University of New Jersey. https://doi.org/10.7282/t3-c6hd-ns81

205. Cai, T., Y. Zhang, X. Ren, L. Bielory, Z. Mi, C.G. Nolte, Y. Gao, L.R. Leung, and P.G. Georgopoulos, 2019: Development of a semi-mechanistic allergenic pollen emission model. *Science of The Total Environment*, **653**, 947–957. https://doi.org/10.1016/j.scitotenv.2018.10.243

206. Cai, T., X. Ren, Z. Mi, L. Bielory, and P.G. Georgopoulos, 2019: Modeling impacts of climate change on population co-exposures to ozone and allergenic pollen across different regions of the United States. In: *APHA's 2019 Annual Meeting and Expo*. 2–6 November 2019. American Public Health Association. https://apha.confex.com/apha/2019/meetingapp.cgi/Paper/447910

207. Zhang, Y., L. Bielory, T. Cai, Z. Mi, and P. Georgopoulos, 2015: Predicting onset and duration of airborne allergenic pollen season in the United States. *Atmospheric Environment*, **103**, 297–306. https://doi.org/10.1016/j.atmosenv.2014.12.019

208. Zhang, Y. and A.L. Steiner, 2022: Projected climate-driven changes in pollen emission season length and magnitude over the continental United States. *Nature Communications*, **13** (1), 1234. https://doi.org/10.1038/s41467-022-28764-0

209. D'Amato, G., H.J. Chong-Neto, O.P. Monge Ortega, C. Vitale, I. Ansotegui, N. Rosario, T. Haahtela, C. Galan, R. Pawankar, M. Murrieta-Aguttes, L. Cecchi, C. Bergmann, E. Ridolo, G. Ramon, S. Gonzalez Diaz, M. D'Amato, and I. Annesi-Maesano, 2020: The effects of climate change on respiratory allergy and asthma induced by pollen and mold allergens. *Allergy*, **75** (9), 2219–2228. https://doi.org/10.1111/all.14476

210. Ren, X., T. Cai, Z. Mi, L. Bielory, C.G. Nolte, and P.G. Georgopoulos, 2022: Modeling past and future spatiotemporal distributions of airborne allergenic pollen across the contiguous United States. *Frontiers in Allergy*, **3**, 959594. https://doi.org/10.3389/falgy.2022.959594

211. Chivato, T., E. Valovirta, R. Dahl, J.d. Monchy, A.B. Thomsen, S. Palkonen, and L. Jacobsen, 2012: Allergy, living and learning: Diagnosis and treatment of allergic respiratory diseases in Europe. *Journal of Investigational Allergology & Clinical Immunology*, **22** (3), 168–179. https://pubmed.ncbi.nlm.nih.gov/22697006/

212. Hesse, L., J.N.G. Oude Elberink, A.J.M. van Oosterhout, and M.C. Nawijn, 2022: Allergen immunotherapy for allergic airway diseases: Use lessons from the past to design a brighter future. *Pharmacology & Therapeutics*, **237**, 108115. https://doi.org/10.1016/j.pharmthera.2022.108115

213. Linares, C., G.S. Martinez, V. Kendrovski, and J. Diaz, 2020: A new integrative perspective on early warning systems for health in the context of climate change. *Environmental Research*, **187**, 109623. https://doi.org/10.1016/j.envres.2020.109623

214. Wikstén, J., S. Toppila-Salmi, and M. Mäkelä, 2018: Primary prevention of airway allergy. *Current Treatment Options in Allergy*, **5** (4), 347–355. https://doi.org/10.1007/s40521-018-0190-4

215. EPA, 2023: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021. EPA 430-R-23-002. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021

216. Thakrar, S.K., S. Balasubramanian, P.J. Adams, I.M.L. Azevedo, N.Z. Muller, S.N. Pandis, S. Polasky, C.A. Pope, A.L. Robinson, J.S. Apte, C.W. Tessum, J.D. Marshall, and J.D. Hill, 2020: Reducing mortality from air pollution in the United States by targeting specific emission sources. *Environmental Science & Technology Letters*, **7** (9), 639–645. https://doi.org/10.1021/acs.estlett.0c00424

217. EPA, 2011: The Benefits and Costs of the Clean Air Act from 1990 to 2020: Summary Report. U.S. Environmental Protection Agency, Office of Air and Radiation, 34 pp. https://www.epa.gov/sites/default/files/2015-07/documents/summaryreport.pdf

218. Hubbell, B.J., R.V. Crume, D.M. Evarts, and J.M. Cohen, 2010: Policy monitor: Regulation and progress under the 1990 Clean Air Act amendments. *Review of Environmental Economics and Policy*, **4** (1), 122–138. https://doi.org/10.1093/reep/rep019

219. Feng, K., S.J. Davis, L. Sun, and K. Hubacek, 2015: Drivers of the US $CO_2$ emissions 1997–2013. *Nature Communications*, **6** (1), 7714. https://doi.org/10.1038/ncomms8714

220. Lamb, W.F., T. Wiedmann, J. Pongratz, R. Andrew, M. Crippa, J.G.J. Olivier, D. Wiedenhofer, G. Mattioli, A.A. Khourdajie, J. House, S. Pachauri, M. Figueroa, Y. Saheb, R. Slade, K. Hubacek, L. Sun, S.K. Ribeiro, S. Khennas, S. de la Rue du Can, L. Chapungu, S.J. Davis, I. Bashmakov, H. Dai, S. Dhakal, X. Tan, Y. Geng, B. Gu, and J. Minx, 2021: A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental Research Letters*, **16** (7), 073005. https://doi.org/10.1088/1748-9326/abee4e

221. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.001

222. Ou, Y., W. Shi, S.J. Smith, C.M. Ledna, J.J. West, C.G. Nolte, and D.H. Loughlin, 2018: Estimating environmental co-benefits of U.S. low-carbon pathways using an integrated assessment model with state-level resolution. *Applied Energy*, **216**, 482–493. https://doi.org/10.1016/j.apenergy.2018.02.122

223. Roth, M.B., P.J. Adams, P. Jaramillo, and N.Z. Muller, 2022: Policy spillovers, technological lock-in, and efficiency gains from regional pollution taxes in the U.S. *Energy and Climate Change*, **3**, 100077. https://doi.org/10.1016/j.egycc.2022.100077

224. Vasilakos, P.N., H. Shen, Q. Mehdi, P. Wilcoxen, C. Driscoll, K. Fallon, D. Burtraw, M. Domeshek, and A.G. Russell, 2022: Us clean energy futures—Air quality benefits of zero carbon energy policies. *Atmosphere*, **13** (9), 1401. https://doi.org/10.3390/atmos13091401

225. Mailloux, N.A., D.W. Abel, T. Holloway, and J.A. Patz, 2022: Nationwide and regional $PM_{2.5}$-related air quality health benefits from the removal of energy-related emissions in the United States. *GeoHealth*, **6** (5), e2022GH000603. https://doi.org/10.1029/2022gh000603

226. Markandya, A., J. Sampedro, S.J. Smith, R. Van Dingenen, C. Pizarro-Irizar, I. Arto, and M. González-Eguino, 2018: Health co-benefits from air pollution and mitigation costs of the Paris Agreement: A modelling study. *The Lancet Planetary Health*, **2** (3), e126–e133. https://doi.org/10.1016/s2542-5196(18)30029-9

227. Nemet, G.F., T. Holloway, and P. Meier, 2010: Implications of incorporating air-quality co-benefits into climate change policymaking. *Environmental Research Letters*, **5** (1), 014007. https://doi.org/10.1088/1748-9326/5/1/014007

228. Shindell, D., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8** (4), 291–295. https://doi.org/10.1038/s41558-018-0108-y

229. Vandyck, T., K. Keramidas, A. Kitous, J.V. Spadaro, R. Van Dingenen, M. Holland, and B. Saveyn, 2018: Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nature Communications*, **9** (1), 4939. https://doi.org/10.1038/s41467-018-06885-9

230. West, J.J., S.J. Smith, R.A. Silva, V. Naik, Y. Zhang, Z. Adelman, M.M. Fry, S. Anenberg, L.W. Horowitz, and J.-F. Lamarque, 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, **3** (10), 885–889. https://doi.org/10.1038/nclimate2009

231. Gallagher, C.L. and T. Holloway, 2020: Integrating air quality and public health benefits in U.S. decarbonization strategies. *Frontiers in Public Health*, **8**, 563358. https://doi.org/10.3389/fpubh.2020.563358

232. Bell, M.L., D.L. Davis, L.A. Cifuentes, A.J. Krupnick, R.D. Morgenstern, and G.D. Thurston, 2008: Ancillary human health benefits of improved air quality resulting from climate change mitigation. *Environmental Health*, **7** (1), 41. https://doi.org/10.1186/1476-069x-7-41

233. Limaye, V.S., W. Max, J. Constible, and K. Knowlton, 2019: Estimating the health-related costs of 10 climate-sensitive U.S. events during 2012. *GeoHealth*, **3** (9), 245–265. https://doi.org/10.1029/2019gh000202

234. Tomlin, A.S., 2021: Air quality and climate impacts of biomass use as an energy source: A review. *Energy & Fuels*, **35** (18), 14213–14240. https://doi.org/10.1021/acs.energyfuels.1c01523

235. Zhang, Y., S.J. Smith, J.H. Bowden, Z. Adelman, and J.J. West, 2017: Co-benefits of global, domestic, and sectoral greenhouse gas mitigation for US air quality and human health in 2050. *Environmental Research Letters*, **12** (11), 114033. https://doi.org/10.1088/1748-9326/aa8f76

236. Mewes, C. and C. Unger, 2021: Learning by doing: Co-benefits drive national plans for climate and air quality governance. *Atmosphere*, **12** (9), 1184. https://doi.org/10.3390/atmos12091184

237. Adan, O.C.G. and R.A. Samson, Eds., 2011: *Fundamentals of Mold Growth in Indoor Environments and Strategies for Healthy Living*. 1st ed., Springer. https://doi.org/10.3920/978-90-8686-722-6

238. Ortiz, M., L. Itard, and P.M. Bluyssen, 2020: Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review. *Energy and Buildings*, **221**, 110102. https://doi.org/10.1016/j.enbuild.2020.110102

239. Shindell, D., J.C.I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S.C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Höglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N.T.K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler, 2012: Simultaneously mitigating near-term climate change and improving human health and food security. *Science*, **335** (6065), 183–189. https://doi.org/10.1126/science.1210026

240. Szopa, S., V. Naik, B. Adhikary, P. Artaxo, T. Berntsen, W.D. Collins, S. Fuzzi, L. Gallardo, A. Kiendler-Scharr, Z. Klimont, H. Liao, N. Unger, and P. Zanis, 2021: Ch. 6. Short-lived climate forcers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 817–922. https://doi.org/10.1017/9781009157896.008

241. West, J.J. and A.M. Fiore, 2005: Management of tropospheric ozone by reducing methane emissions. *Environmental Science & Technology*, **39** (13), 4685–4691. https://doi.org/10.1021/es048629f

242. IWG, 2021: Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide—Interim Estimates under Executive Order 13990. U.S. Government, Interagency Working Group on Social Cost of Greenhouse Gases. https://www.whitehouse.gov/wp-content/uploads/2021/02/technicalsupportdocument_socialcostofcarbonmethanenitrousoxide.pdf

243. Shindell, D.T., J.S. Fuglestvedt, and W.J. Collins, 2017: The social cost of methane: Theory and applications. *Faraday Discussions*, **200**, 429–451. https://doi.org/10.1039/c7fd00009j

244. UNEP and Climate and Clean Air Coalition, 2021: Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. United Nations Environment Programme, Nairobi, Kenya. https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions

245. Sarofim, M.C., S.T. Waldhoff, and S.C. Anenberg, 2017: Valuing the ozone-related health benefits of methane emission controls. *Environmental and Resource Economics*, **66** (1), 45–63. https://doi.org/10.1007/s10640-015-9937-6

246. Fry, M.M., V. Naik, J.J. West, M.D. Schwarzkopf, A.M. Fiore, W.J. Collins, F.J. Dentener, D.T. Shindell, C. Atherton, D. Bergmann, B.N. Duncan, P. Hess, I.A. MacKenzie, E. Marmer, M.G. Schultz, S. Szopa, O. Wild, and G. Zeng, 2012: The influence of ozone precursor emissions from four world regions on tropospheric composition and radiative climate forcing. *Journal of Geophysical Research: Atmospheres*, **117** (D7). https://doi.org/10.1029/2011jd017134

247. IPCC, 2021: Summary for policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–32. https://doi.org/10.1017/9781009157896.001

248. Dvorak, M.T., K.C. Armour, D.M.W. Frierson, C. Proistosescu, M.B. Baker, and C.J. Smith, 2022: Estimating the timing of geophysical commitment to 1.5 and 2.0 °C of global warming. *Nature Climate Change*, **12** (6), 547–552. https://doi.org/10.1038/s41558-022-01372-y

249. Leibensperger, E.M., L.J. Mickley, D.J. Jacob, W.T. Chen, J.H. Seinfeld, A. Nenes, P.J. Adams, D.G. Streets, N. Kumar, and D. Rind, 2012: Climatic effects of 1950–2050 changes in US anthropogenic aerosols—Part 2: Climate response. *Atmospheric Chemistry and Physics*, **12** (7), 3349–3362. https://doi.org/10.5194/acp-12-3349-2012

250. Westervelt, D.M., A.M. Fiore, C.B. Baublitz, and G. Correa, 2021: Impact of regional Northern Hemisphere mid-latitude anthropogenic sulfur dioxide emissions on local and remote tropospheric oxidants. *Atmospheric Chemistry and Physics*, **21** (9), 6799–6810. https://doi.org/10.5194/acp-21-6799-2021

251. Zheng, Y., S.J. Davis, G.G. Persad, and K. Caldeira, 2020: Climate effects of aerosols reduce economic inequality. *Nature Climate Change*, **10** (3), 220–224. https://doi.org/10.1038/s41558-020-0699-y

252. Dreyfus, G.B., Y. Xu, D.T. Shindell, D. Zaelke, and V. Ramanathan, 2022: Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (22), e2123536119. https://doi.org/10.1073/pnas.2123536119

253. Shindell, D. and C.J. Smith, 2019: Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature*, **573** (7774), 408–411. https://doi.org/10.1038/s41586-019-1554-z

254. Domingo, N.G.G., S. Balasubramanian, S.K. Thakrar, M.A. Clark, P.J. Adams, J.D. Marshall, N.Z. Muller, S.N. Pandis, S. Polasky, A.L. Robinson, C.W. Tessum, D. Tilman, P. Tschofen, and J.D. Hill, 2021: Air quality–related health damages of food. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (20), e2013637118. https://doi.org/10.1073/pnas.2013637118

255. Powell, J.M., C.J.P. Gourley, C.A. Rotz, and D.M. Weaver, 2010: Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. *Environmental Science & Policy*, **13** (3), 217–228. https://doi.org/10.1016/j.envsci.2010.03.007

256. Robertson, G.P. and P.M. Vitousek, 2009: Nitrogen in agriculture: Balancing the cost of an essential resource. *Annual Review of Environment and Resources*, **34** (1), 97–125. https://doi.org/10.1146/annurev.environ.032108.105046

257. Hitaj, C., S. Rehkamp, P. Canning, and C.J. Peters, 2019: Greenhouse gas emissions in the United States food system: Current and healthy diet scenarios. *Environmental Science & Technology*, **53** (9), 5493–5503. https://doi.org/10.1021/acs.est.8b06828

258. Ramanathan, V. and G. Carmichael, 2008: Global and regional climate changes due to black carbon. *Nature Geoscience*, **1** (4), 221–227. https://doi.org/10.1038/ngeo156

259. Archibald, A.T., S.T. Turnock, P.T. Griffiths, T. Cox, R.G. Derwent, C. Knote, and M. Shin, 2020: On the changes in surface ozone over the twenty-first century: Sensitivity to changes in surface temperature and chemical mechanisms. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **378** (2183), 20190329. https://doi.org/10.1098/rsta.2019.0329

260. Porter, W.C. and C.L. Heald, 2019: The mechanisms and meteorological drivers of the summertime ozone–temperature relationship. *Atmospheric Chemistry and Physics*, **19** (21), 13367–13381. https://doi.org/10.5194/acp-19-13367-2019

261. NADP, 2022: National Atmospheric Deposition Program [Website], accessed August 7, 2023. https://nadp.slh.wisc.edu/

262. Anenberg, S.C., M. Bindl, M. Brauer, J.J. Castillo, S. Cavalieri, B.N. Duncan, A.M. Fiore, R. Fuller, D.L. Goldberg, D.K. Henze, J. Hess, T. Holloway, P. James, X. Jin, I. Kheirbek, P.L. Kinney, Y. Liu, A. Mohegh, J. Patz, M.P. Jimenez, A. Roy, D. Tong, K. Walker, N. Watts, and J.J. West, 2020: Using Satellites to Track Indicators of Global Air Pollution and Climate Change Impacts: Lessons Learned From a NASA-Supported Science-Stakeholder Collaborative. *GeoHealth*, **4** (7), e2020GH000270. https://doi.org/10.1029/2020GH000270

263. Zoogman, P., X. Liu, R.M. Suleiman, W.F. Pennington, D.E. Flittner, J.A. Al-Saadi, B.B. Hilton, D.K. Nicks, M.J. Newchurch, J.L. Carr, S.J. Janz, M.R. Andraschko, A. Arola, B.D. Baker, B.P. Canova, C. Chan Miller, R.C. Cohen, J.E. Davis, M.E. Dussault, D.P. Edwards, J. Fishman, A. Ghulam, G. González Abad, M. Grutter, J.R. Herman, J. Houck, D.J. Jacob, J. Joiner, B.J. Kerridge, J. Kim, N.A. Krotkov, L. Lamsal, C. Li, A. Lindfors, R.V. Martin, C.T. McElroy, C. McLinden, V. Natraj, D.O. Neil, C.R. Nowlan, E.J. O□Sullivan, P.I. Palmer, R.B. Pierce, M.R. Pippin, A. Saiz-Lopez, R.J.D. Spurr, J.J. Szykman, O. Torres, J.P. Veefkind, B. Veihelmann, H. Wang, J. Wang, and K. Chance, 2017: Tropospheric Emissions: Monitoring of Pollution (TEMPO). *Journal of Quantitative Spectroscopy and Radiative Transfer*, **186**, 17–39. https://doi.org/10.1016/j.jqsrt.2016.05.008

264. Li, Y., L.J. Mickley, P. Liu, and J.O. Kaplan, 2020: Trends and spatial shifts in lightning fires and smoke concentrations in response to 21st century climate over the national forests and parks of the western United States. *Atmospheric Chemistry and Physics*, **20** (14), 8827–8838. https://doi.org/10.5194/acp-20-8827-2020

265. Dosio, A., L. Mentaschi, E.M. Fischer, and K. Wyser, 2018: Extreme heat waves under 1.5°C and 2°C global warming. *Environmental Research Letters*, **13** (5), 054006. https://doi.org/10.1088/1748-9326/aab827

266. Porter, W.C., C.L. Heald, D. Cooley, and B. Russell, 2015: Investigating the observed sensitivities of air-quality extremes to meteorological drivers via quantile regression. *Atmospheric Chemistry and Physics*, **15** (18), 10349–10366. https://doi.org/10.5194/acp-15-10349-2015

267. Li, W., Y. Wang, J. Flynn, R.J. Griffin, F. Guo, and J.L. Schnell, 2022: Spatial variation of surface $O_3$ responses to drought over the contiguous United States during summertime: Role of precursor emissions and ozone chemistry. *Journal of Geophysical Research: Atmospheres*, **127** (1), e2021JD035607. https://doi.org/10.1029/2021jd035607

268. Naimark, J.G., A.M. Fiore, X. Jin, Y. Wang, E. Klovenski, and C. Braneon, 2021: Evaluating drought responses of surface ozone precursor proxies: Variations with land cover type, precipitation, and temperature. *Geophysical Research Letters*, **48** (7), e2020GL091520. https://doi.org/10.1029/2020gl091520

269. Zheng, Y., N. Unger, J.M. Tadić, R. Seco, A.B. Guenther, M.P. Barkley, M.J. Potosnak, L.T. Murray, A.M. Michalak, X. Qiu, S. Kim, T. Karl, L. Gu, and S.G. Pallardy, 2017: Drought impacts on photosynthesis, isoprene emission and atmospheric formaldehyde in a mid-latitude forest. *Atmospheric Environment*, **167**, 190–201. https://doi.org/10.1016/j.atmosenv.2017.08.017

270. Lin, M., L.W. Horowitz, R. Payton, A.M. Fiore, and G. Tonnesen, 2017: US surface ozone trends and extremes from 1980 to 2014: Quantifying the roles of rising Asian emissions, domestic controls, wildfires, and climate. *Atmospheric Chemistry and Physics*, **17** (4), 2943–2970. https://doi.org/10.5194/acp-17-2943-2017

271. Wang, Y., Y. Xie, W. Dong, Y. Ming, J. Wang, and L. Shen, 2017: Adverse effects of increasing drought on air quality via natural processes. *Atmospheric Chemistry and Physics*, **17** (20), 12827–12843. https://doi.org/10.5194/acp-17-12827-2017

272. Almazroui, M., M.N. Islam, F. Saeed, S. Saeed, M. Ismail, M.A. Ehsan, I. Diallo, E. O'Brien, M. Ashfaq, D. Martínez-Castro, T. Cavazos, R. Cerezo-Mota, M.K. Tippett, W.J. Gutowski, E.J. Alfaro, H.G. Hidalgo, A. Vichot-Llano, J.D. Campbell, S. Kamil, I.U. Rashid, M.B. Sylla, T. Stephenson, M. Taylor, and M. Barlow, 2021: Projected changes in temperature and precipitation over the United States, Central America, and the Caribbean in CMIP6 GCMs. *Earth Systems and Environment*, **5** (1), 1–24. https://doi.org/10.1007/s41748-021-00199-5

273. Douville, H., K. Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T.Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina, 2021: Ch. 8. Water cycle changes. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1055–1210. https://doi.org/10.1017/9781009157896.010

274. Johnson, C.E., W.J. Collins, D.S. Stevenson, and R.G. Derwent, 1999: Relative roles of climate and emissions changes on future tropospheric oxidant concentrations. *Journal of Geophysical Research: Atmospheres*, **104** (D15), 18631–18645. https://doi.org/10.1029/1999jd900204

275. Tai, A.P.K., L.J. Mickley, and D.J. Jacob, 2010: Correlations between fine particulate matter ($PM_{2.5}$) and meteorological variables in the United States: Implications for the sensitivity of $PM_{2.5}$ to climate change. *Atmospheric Environment*, **44** (32), 3976–3984. https://doi.org/10.1016/j.atmosenv.2010.06.060

276. Doherty, R.M., O. Wild, D.T. Shindell, G. Zeng, I.A. MacKenzie, W.J. Collins, A.M. Fiore, D.S. Stevenson, F.J. Dentener, M.G. Schultz, P. Hess, R.G. Derwent, and T.J. Keating, 2013: Impacts of climate change on surface ozone and intercontinental ozone pollution: A multi-model study. *Journal of Geophysical Research: Atmospheres*, **118** (9), 3744–3763. https://doi.org/10.1002/jgrd.50266

277. Horton, D.E., C.B. Skinner, D. Singh, and N.S. Diffenbaugh, 2014: Occurrence and persistence of future atmospheric stagnation events. *Nature Climate Change*, **4** (8), 698–703. https://doi.org/10.1038/nclimate2272

278. Kalashnikov, D.A., J.L. Schnell, J.T. Abatzoglou, D.L. Swain, and D. Singh, 2022: Increasing co-occurrence of fine particulate matter and ground-level ozone extremes in the western United States. *Science Advances*, **8** (1), 9386. https://doi.org/10.1126/sciadv.abi9386

279. Garcia-Menendez, F., E. Monier, and N.E. Selin, 2017: The role of natural variability in projections of climate change impacts on U.S. ozone pollution. *Geophysical Research Letters*, **44** (6), 2911–2921. https://doi.org/10.1002/2016gl071565

280. Fiore, A.M., G.P. Milly, S.E. Hancock, L. Quiñones, J.H. Bowden, E. Helstrom, J.-F. Lamarque, J. Schnell, J.J. West, and Y. Xu, 2022: Characterizing changes in eastern U.S. pollution events in a warming world. *Journal of Geophysical Research*, **127**, e2021JD035985. https://doi.org/10.1029/2021jd035985

281. Fiore, A.M., J.J. West, L.W. Horowitz, V. Naik, and M.D. Schwarzkopf, 2008: Characterizing the tropospheric ozone response to methane emission controls and the benefits to climate and air quality. *Journal of Geophysical Research: Atmospheres*, **113** (D8). https://doi.org/10.1029/2007jd009162

282. Barnes, E.A., A.M. Fiore, and L.W. Horowitz, 2016: Detection of trends in surface ozone in the presence of climate variability. *Journal of Geophysical Research: Atmospheres*, **121** (10), 6112–6129. https://doi.org/10.1002/2015jd024397

283. Shen, L. and L.J. Mickley, 2017: Effects of El Niño on summertime ozone air quality in the eastern United States. *Geophysical Research Letters*, **44** (24), 12543–12550. https://doi.org/10.1002/2017gl076150

284. Shen, L., L.J. Mickley, E.M. Leibensperger, and M. Li, 2017: Strong dependence of U.S. summertime air quality on the decadal variability of Atlantic sea surface temperatures. *Geophysical Research Letters*, **44** (24), 12527–12535. https://doi.org/10.1002/2017gl075905

285. EPA, 2019: Integrated Science Assessment (ISA) for Particulate Matter (Final Report, Dec 2019). EPA/600/R-19/188. U.S. Environmental Protection Agency, Washington, DC. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=347534

286. Doherty, R.M., F.M. O'Connor, and S.T. Turnock, 2022: Projections of future air quality are uncertain. But which source of uncertainty is most important? *Journal of Geophysical Research: Atmospheres*, **127** (21), e2022JD037948. https://doi.org/10.1029/2022jd037948

287. East, J.D., E. Monier, and F. Garcia-Menendez, 2022: Characterizing and quantifying uncertainty in projections of climate change impacts on air quality. *Environmental Research Letters*, **17** (9), 094042. https://doi.org/10.1088/1748-9326/ac8d17

288. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. https://doi.org/10.1038/s41558-022-01290-z

289. Lassman, W., B. Ford, R.W. Gan, G. Pfister, S. Magzamen, E.V. Fischer, and J.R. Pierce, 2017: Spatial and temporal estimates of population exposure to wildfire smoke during the Washington state 2012 wildfire season using blended model, satellite, and in situ data. *GeoHealth*, **1** (3), 106–121. https://doi.org/10.1002/2017gh000049

290. Liu, J.C., A. Wilson, L.J. Mickley, F. Dominici, K. Ebisu, Y. Wang, M.P. Sulprizio, R.D. Peng, X. Yue, J.-Y. Son, G.B. Anderson, and M.L. Bell, 2017: Wildfire-specific fine particulate matter and risk of hospital admissions in urban and rural counties. *Epidemiology*, **28** (1), 77–85. https://doi.org/10.1097/ede.0000000000000556

291. Ahmadov, R., G. Grell, E. James, I. Csiszar, M. Tsidulko, B. Pierce, S. McKeen, S. Benjamin, C. Alexander, G. Pereira, S. Freitas, and M. Goldberg, 2017: Using VIIRS fire radiative power data to simulate biomass burning emissions, plume rise and smoke transport in a real-time air quality modeling system. In: *2017 IEEE International Geoscience and Remote Sensing Symposium* (IGARSS). Fort Worth, TX, 23–28 July 2017. IEEE. https://doi.org/10.1109/igarss.2017.8127581

292. Larkin, N.K., S.M. O'Neill, R. Solomon, S. Raffuse, T. Strand, D.C. Sullivan, C. Krull, M. Rorig, J. Peterson, and S.A. Ferguson, 2009: The BlueSky smoke modeling framework. *International Journal of Wildland Fire*, **18** (8), 906–920. https://doi.org/10.1071/wf07086

293. Odman, M.T., R. Huang, A.A. Pophale, R.D. Sakhpara, Y. Hu, A.G. Russell, and M.E. Chang, 2018: Forecasting the impacts of prescribed fires for dynamic air quality management. *Atmosphere*, **9** (6), 220. https://doi.org/10.3390/atmos9060220

294. Vaughan, J., B. Lamb, C. Frei, R. Wilson, C. Bowman, C. Figueroa-Kaminsky, S. Otterson, M. Boyer, C. Mass, M. Albright, J. Koenig, A. Collingwood, M. Gilroy, and N. Maykut, 2004: A numerical daily air quality forecast system for the Pacific Northwest. *Bulletin of the American Meteorological Society*, **85** (4), 549–562. https://doi.org/10.1175/bams-85-4-549

295. City of Ashland Oregon, 2019: Smokewise Ashland [Website]. https://www.ashland.or.us/sectionindex.asp?sectionid=534

296. Colville Tribes, 2022: Wildfire Smoke. The Confederated Tribes of the Colville Reservation. https://www.cct-enr.com/smoke

297. Missoula City-County Health Department, 2022: Wildfire Smoke [Webpage]. Missoula County, MT. https://www.missoulacounty.us/government/health/health-department/home-environment/air-quality/wildfire-smoke

298. State of California, 2021: Protecting Outdoor Workers Exposed to Smoke from Wildfires. State of California, Department of Industrial Relations. https://www.dir.ca.gov/dosh/wildfire/worker-protection-from-wildfire-smoke.html

299. California Smoke Information, 2022: California smoke information [Blog]. http://californiasmokeinfo.blogspot.com/

300. Idaho Smoke Information, 2022: Idaho smoke information [Blog]. http://idsmoke.blogspot.com/

301. Oregon DEQ, 2022: Oregon Smoke Information. Oregon Department of Environmental Quality. https://www.oregonsmoke.org/

302. Washington Smoke Information, 2022: Washington smoke information [Blog]. https://wasmoke.blogspot.com/

303. Laumbach, R.J., 2019: Clearing the air on personal interventions to reduce exposure to wildfire smoke. *Annals of the American Thoracic Society*, **16** (7), 815–818. https://doi.org/10.1513/annalsats.201812-894ps

304. Reisen, F., J.C. Powell, M. Dennekamp, F.H. Johnston, and A.J. Wheeler, 2019: Is remaining indoors an effective way of reducing exposure to fine particulate matter during biomass burning events? *Journal of the Air & Waste Management Association*, **69** (5), 611–622. https://doi.org/10.1080/10962247.2019.1567623

305. Commodore, A., S. Wilson, O. Muhammad, E. Svendsen, and J. Pearce, 2017: Community-based participatory research for the study of air pollution: A review of motivations, approaches, and outcomes. *Environmental Monitoring and Assessment*, **189** (8), 378. https://doi.org/10.1007/s10661-017-6063-7

306. Do, T.H., E. Tsiligianni, X. Qin, J. Hofman, V.P.L. Manna, W. Philips, and N. Deligiannis, 2020: Graph-deep-learning-based inference of fine-grained air quality from mobile IoT sensors. *IEEE Internet of Things Journal*, **7** (9), 8943–8955. https://doi.org/10.1109/jiot.2020.2999446

307. Ezeugoh, R.I., R. Puett, D. Payne-Sturges, R. Cruz-Cano, and S.M. Wilson, 2019: Air quality assessment of volatile organic compounds near a concrete block plant and traffic in Bladensburg, Maryland. *Environmental Justice*, **12** (6), 250–260. https://doi.org/10.1089/env.2019.0017

308. Ezeugoh, R.I., R. Puett, D. Payne-Sturges, R. Cruz-Cano, and S.M. Wilson, 2020: Air quality assessment of particulate matter near a concrete block plant and traffic in Bladensburg, Maryland. *Environmental Justice*, **13** (3), 75–85. https://doi.org/10.1089/env.2020.0005

309. Masri, S., K. Cox, L. Flores, J. Rea, and J. Wu, 2022: Community-engaged use of low-cost sensors to assess the spatial distribution of $PM_{2.5}$ concentrations across disadvantaged communities: Results from a pilot study in Santa Ana, CA. *Atmosphere*, **13** (2), 304. https://doi.org/10.3390/atmos13020304

310. Pearce, J., A. Commodore, B. Neelon, R. Boaz, M. Bozigar, S. Wilson, and E. Svendsen, 2017: A novel approach for characterizing neighborhood-level trends in particulate matter using concentration and size fraction distributions: A case study in Charleston, SC. *Air Quality, Atmosphere & Health*, **10** (10), 1181–1192. https://doi.org/10.1007/s11869-017-0503-y

311. Wallace, L., 2022: Intercomparison of PurpleAir sensor performance over three years indoors and outdoors at a home: Bias, precision, and limit of detection using an improved algorithm for calculating $PM_{2.5}$. *Sensors*, **22** (7), 2755. https://doi.org/10.3390/s22072755

312. Kerr, G.H., D.L. Goldberg, and S.C. Anenberg, 2021: COVID-19 pandemic reveals persistent disparities in nitrogen dioxide pollution. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (30), e2022409118. https://doi.org/10.1073/pnas.2022409118

313. Clark, L.P., D.B. Millet, and J.D. Marshall, 2014: National patterns in environmental injustice and inequality: Outdoor $NO_2$ air pollution in the United States. *PLoS ONE*, **9** (4), e94431. https://doi.org/10.1371/journal.pone.0094431

314. Southerland, V.A., S.C. Anenberg, M. Harris, J. Apte, P. Hystad, A. van Donkelaar, R.V. Martin, M. Beyers, and A. Roy, 2021: Assessing the distribution of air pollution health risks within cities: A neighborhood-scale analysis leveraging high-resolution data sets in the Bay Area, California. *Environmental Health Perspectives*, **129** (3), 037006. https://doi.org/10.1289/ehp7679

315. Apte, J.S., K.P. Messier, S. Gani, M. Brauer, T.W. Kirchstetter, M.M. Lunden, J.D. Marshall, C.J. Portier, R.C.H. Vermeulen, and S.P. Hamburg, 2017: High-resolution air pollution mapping with Google street view cars: Exploiting big data. *Environmental Science & Technology*, **51** (12), 6999–7008. https://doi.org/10.1021/acs.est.7b00891

316. Kelly, J.T., C. Jang, B. Timin, Q. Di, J. Schwartz, Y. Liu, A. van Donkelaar, R.V. Martin, V. Berrocal, and M.L. Bell, 2021: Examining $PM_{2.5}$ concentrations and exposure using multiple models. *Environmental Research*, **196**, 110432. https://doi.org/10.1016/j.envres.2020.110432

317. Nguyen, N.P. and J.D. Marshall, 2018: Impact, efficiency, inequality, and injustice of urban air pollution: Variability by emission location. *Environmental Research Letters*, **13** (2), 024002. https://doi.org/10.1088/1748-9326/aa9cb5

318. Chambliss, S.E., C.P.R. Pinon, K.P. Messier, B. LaFranchi, C.R. Upperman, M.M. Lunden, A.L. Robinson, J.D. Marshall, and J.S. Apte, 2021: Local- and regional-scale racial and ethnic disparities in air pollution determined by long-term mobile monitoring. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (37), e2109249118. https://doi.org/10.1073/pnas.2109249118

319. Morello-Frosch, R. and B.M. Jesdale, 2006: Separate and unequal: Residential segregation and estimated cancer risks associated with ambient air toxics in U.S. metropolitan areas. *Environmental Health Perspectives*, **114** (3), 386–393. https://doi.org/10.1289/ehp.8500

320. Piao, S., Q. Liu, A. Chen, I.A. Janssens, Y. Fu, J. Dai, L. Liu, X. Lian, M. Shen, and X. Zhu, 2019: Plant phenology and global climate change: Current progresses and challenges. *Global Change Biology*, **25** (6), 1922–1940. https://doi.org/10.1111/gcb.14619

321. Sapkota, A., R. Murtugudde, F.C. Curriero, C.R. Upperman, L. Ziska, and C. Jiang, 2019: Associations between alteration in plant phenology and hay fever prevalence among US adults: Implication for changing climate. *PLoS ONE*, **14** (3), e0212010. https://doi.org/10.1371/journal.pone.0212010

322. Stone, E.A., C.B.A. Mampage, D.D. Hughes, and L.M. Jones, 2021: Airborne sub-pollen particles from rupturing giant ragweed pollen. *Aerobiologia*, **37** (3), 625–632. https://doi.org/10.1007/s10453-021-09702-x

323. Tasioulis, T., K. Karatzas, A. Charalampopoulos, A. Damialis, and D. Vokou, 2022: Five ways to define a pollen season: Exploring congruence and disparity in its attributes and their long-term trends. *Aerobiologia*, **38** (1), 71–83. https://doi.org/10.1007/s10453-021-09735-2

324. Schramm, P.J., C.L. Brown, S. Saha, K.C. Conlon, A.P. Manangan, J.E. Bell, and J.J. Hess, 2021: A systematic review of the effects of temperature and precipitation on pollen concentrations and season timing, and implications for human health. *International Journal of Biometeorology*, **65** (10), 1615–1628. https://doi.org/10.1007/s00484-021-02128-7

325. Efstathiou, C., S. Isukapalli, and P. Georgopoulos, 2011: A mechanistic modeling system for estimating large-scale emissions and transport of pollen and co-allergens. *Atmospheric Environment*, **45** (13), 2260–2276. https://doi.org/10.1016/j.atmosenv.2010.12.008

326. Zhang, R., T. Duhl, M.T. Salam, J.M. House, R.C. Flagan, E.L. Avol, F.D. Gilliland, A. Guenther, S.H. Chung, B.K. Lamb, and T.M. VanReken, 2014: Development of a regional-scale pollen emission and transport modeling framework for investigating the impact of climate change on allergic airway disease. *Biogeosciences*, **11** (6), 1461–1478. https://doi.org/10.5194/bg-11-1461-2014

327. Li, W., Q. Xin, X. Zhou, Z. Zhang, and Y. Ruan, 2021: Comparisons of numerical phenology models and machine learning methods on predicting the spring onset of natural vegetation across the Northern Hemisphere. *Ecological Indicators*, **131**, 108126. https://doi.org/10.1016/j.ecolind.2021.108126

328. Lo, F., C.M. Bitz, and J.J. Hess, 2021: Development of a random forest model for forecasting allergenic pollen in North America. *Science of The Total Environment*, **773**, 145590. https://doi.org/10.1016/j.scitotenv.2021.145590

329. Schaefer, J., M. Milling, B.W. Schuller, B. Bauer, J.O. Brunner, C. Traidl-Hoffmann, and A. Damialis, 2021: Towards automatic airborne pollen monitoring: From commercial devices to operational by mitigating class-imbalance in a deep learning approach. *Science of The Total Environment*, **796**, 148932. https://doi.org/10.1016/j.scitotenv.2021.148932

330. Sevillano, V., K. Holt, and J.L. Aznarte, 2020: Precise automatic classification of 46 different pollen types with convolutional neural networks. *PLoS ONE*, **15** (6), e0229751. https://doi.org/10.1371/journal.pone.0229751

331. Holloway, T., D. Miller, S. Anenberg, M. Diao, B. Duncan, A.M. Fiore, D.K. Henze, J. Hess, P.L. Kinney, Y. Liu, J.L. Neu, S.M. O'Neill, M.T. Odman, R.B. Pierce, A.G. Russell, D. Tong, J.J. West, and M.A. Zondlo, 2021: Satellite monitoring for air quality and health. *Annual Review of Biomedical Data Science*, **4** (1), 417–447. https://doi.org/10.1146/annurev-biodatasci-110920-093120

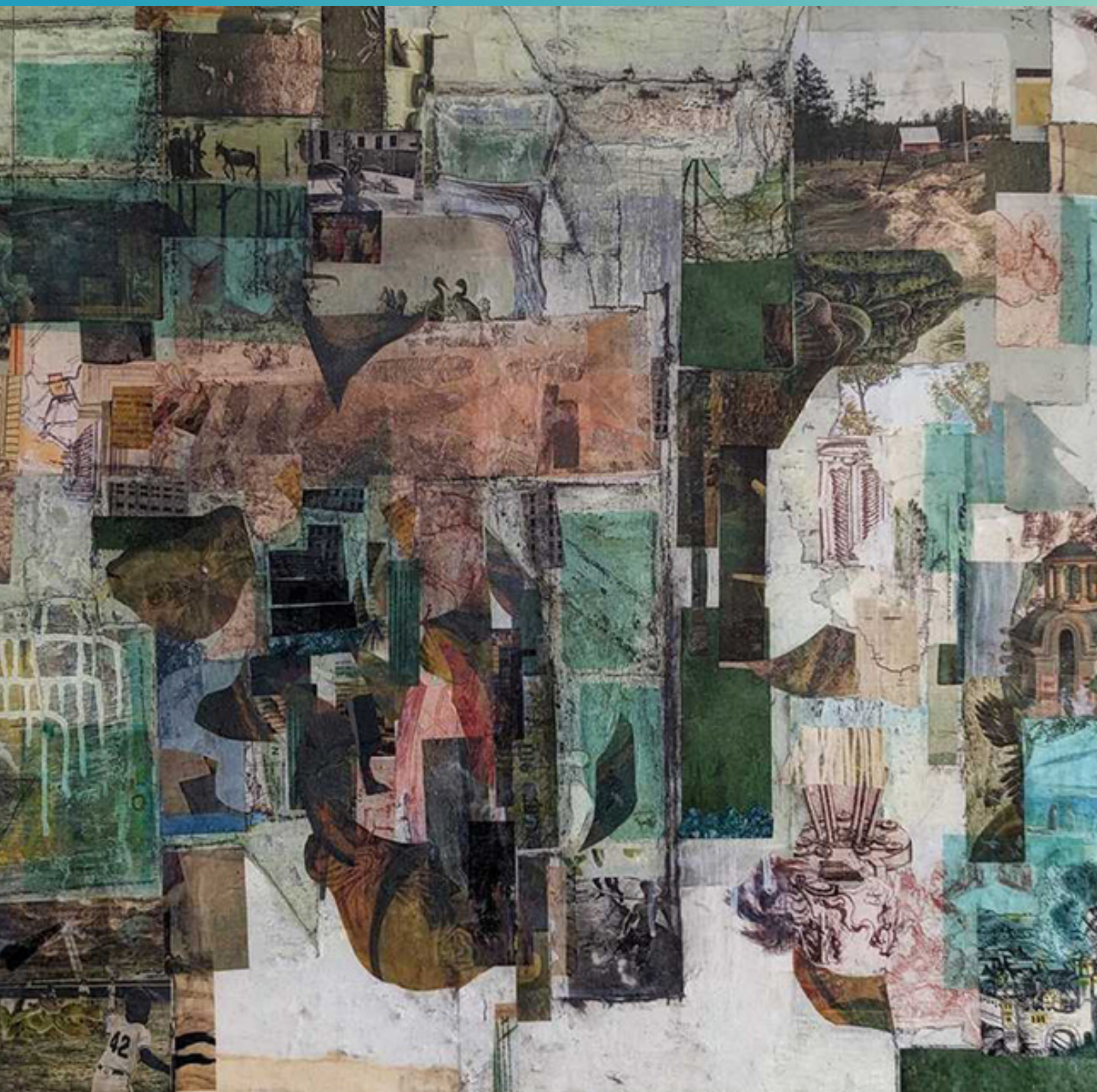
332. Li, L., D. Hao, X. Li, M. Chen, Y. Zhou, D. Jurgens, G. Asrar, and A. Sapkota, 2022: Satellite-based phenology products and in-situ pollen dynamics: A comparative assessment. *Environmental Research*, **204**, 111937. https://doi.org/10.1016/j.envres.2021.111937

333. EPA, 2021: 2017 National Emissions Inventory: January 2021 Updated Release, Technical Support Document. EPA-454/R-21-001. U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2021-02/documents/nei2017_tsd_full_jan2021.pdf

334. EPA, 2022: Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances. U.S. Environmental Protection Agency, Washington, DC. https://www.epa.gov/system/files/documents/2022-11/epa_scghg_report_draft_0.pdf

Fifth National Climate Assessment: Chapter 15

# Human Health



# Chapter 15. Human Health

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# Introduction

Climate change has profound negative effects on human health. Climate-related extreme events that impact the US population include floods, droughts, wildfires, extreme temperatures, and storms. All are expected to increase in frequency, intensity, and extent (KM 2.2). Health risks from a changing climate include higher rates of heat-related morbidity and mortality; increases in the geographic range of some infectious diseases; greater exposure to poor air quality; increases in some adverse pregnancy outcomes; higher rates of pulmonary, neurological, and cardiovascular diseases; and worsening mental health.[1,2,3,4,5,6,7] These risks affect all US residents but have disproportionate repercussions for under-resourced and overburdened communities and individuals, such as pregnant people, communities of color, children, people with disabilities, people experiencing homelessness, people with chronic diseases, and older adults. Structural racism and discrimination against groups that have been marginalized play a direct role in health inequities and are public health crises.[8] Existing and projected human health impacts of climate change affect populations that are already experiencing an unprecedented decline in life expectancy due to environmental, social, political, and economic conditions that determine community health and well-being.[9,10,11] Creating climate-resilient health systems, implementing adaptation measures, and mitigating greenhouse gas (GHG) emissions can protect human health.

## Key Message 15.1

## Climate Change Is Harming Human Health

It is an established fact that climate change is harming physical, mental, spiritual, and community health and well-being through the increasing frequency and intensity of extreme events, increasing cases of infectious and vector-borne diseases, and declines in food and water quality and security. Climate-related hazards will continue to grow, increasing morbidity and mortality across all regions of the US (*very likely, very high confidence*).

### *Extreme Heat*

In recent decades, rising temperatures have increased heat-related health impacts in the US (Figures 21.8, 22.9, 25.3, 26.2, 27.8, 28.7; KM 2.2).[12] Higher temperatures are associated with adverse pregnancy and birth outcomes, mental health impacts, and increased emergency room visits and hospitalizations related to cardiovascular disease, diabetes, electrolyte imbalance, renal failure, and respiratory outcomes.[13,14,15] Heat-related health impacts are greatest among children, adults over age 65, those with disabilities, people with mental health or substance-use disorders; and those who are pregnant, lack access to cooling, or engage in outdoor labor and activities (Figure 15.1).[13,16,17,18,19] Black, Latinx, Asian, historically redlined, and urban communities are disproportionately exposed to heat, as are those with low wealth and people experiencing homelessness (Figures 12.4, 12.6; KM 22.2);[20,21,22] these groups also report being more worried about heat risks.[23,24,25] Certain medications for management of cardiovascular conditions and mental health disorders may accentuate heat-health risk.[26,27] Heat-related death and illness will continue to increase unless climate change adaptation and mitigation policies are implemented (KM 15.3).[28,29]

## Heat and Health Equity

**Heat does not impact all communities equally.**

**Figure 15.1.** While anyone can be impacted by heat, location, economics, compound risks, and social and racial factors influence who is most at risk. These impacts disproportionately affect BIPOC (Black, Indigenous, and People of Color) communities as well as communities with low wealth. Figure credit: CDC, University of Colorado, NOAA NCEI, and CISESS NC. Image credits (clockwise from top left): NIEHS/Kelly Government Solutions and USGS/ASRC Federal Data Solutions; FG Trade/E+ via Getty Images; YinYang/E+ via Getty Images; Marc Dufresne/iStock via Getty Images.

## *Drought*

Among weather and climate disasters in the US over the last 40 years that have caused more than a billion dollars of economic loss, drought is responsible for the second-highest number of climate-related deaths—approximately 99 per year (Figure A4.9).[30] However, these statistics probably underreport the total number of deaths, as these estimates account only for heat-related mortality that accompanies droughts.[31] There is growing evidence of an association between drought and increased mortality in adults ages 25–64 in both rural and urban populations.[32,33] Drought can worsen air quality, resulting in adverse health outcomes such as increased cardiovascular and pulmonary disease and premature death (KM 4.2).[34,35] It can also decrease water quantity and quality, which can cause increased exposure to heavy metals, bacteria, and other harmful contaminants (KMs 30.2, 30.2).[36,37,38] Because farmers rely on the land for their livelihood, drought during the growing season is associated with worsening mental health among rural US farmers (KMs 11.2, 22.4).[39]

## *Wildfires*

Wildfire activity has significantly increased over the last few decades, especially in the western US (KM 14.2; Figure 28.9; Focus on Western Wildfires). Roughly half of the increase in burned areas in the US can be attributed to a warming climate.[40] Wildfires and resulting poor air quality can cause disruptions to a person's life, including loss of livelihood and displacement, and can lead to multiple adverse health effects, including death, illnesses, injuries, adverse reproductive outcomes, poor mental health consequences, and declines in

psychosocial well-being.[41,42,43,44] Exposure to smoke from wildfires is associated with emergency department visits, hospitalizations, and deaths.[45,46,47,48,49]

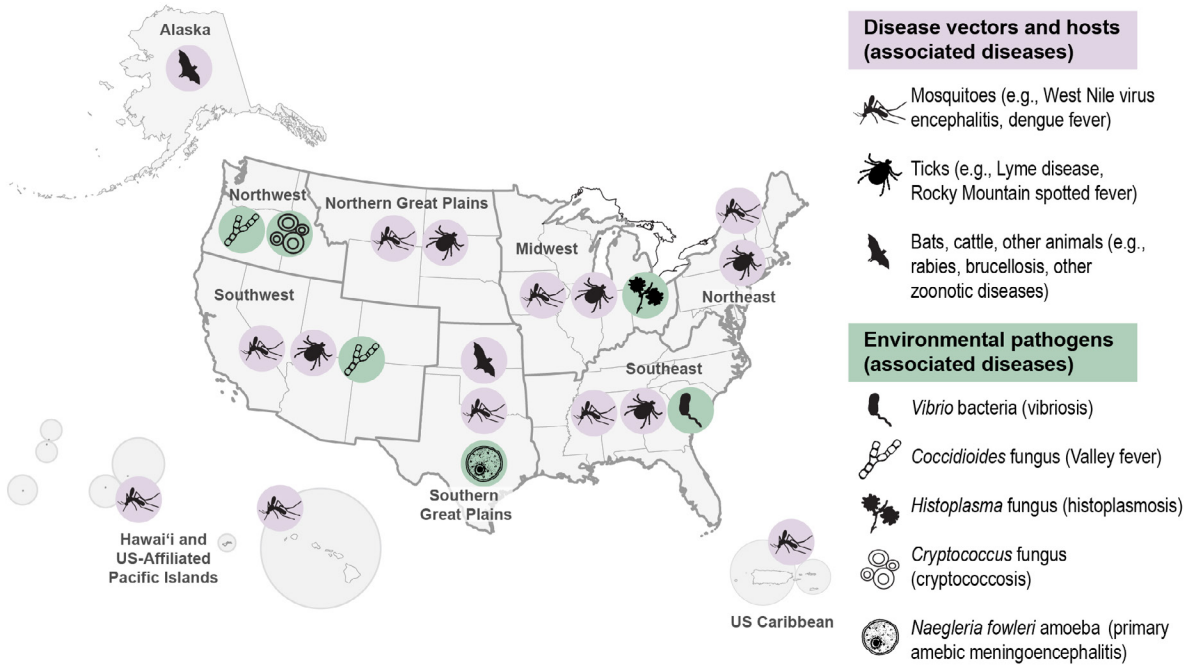
## *Infectious Diseases*

Climate change is expected to alter the distribution, abundance, and seasonality of pathogens and their associated infections (Figure 15.2; Focus on COVID-19 and Climate Change).[50,51,52,53] The range of vampire bats in Texas and Florida is expected to increase due to rising temperatures, which can lead to increased human rabies exposure.[54,55] Exposure to rabies and other zoonoses like brucellosis and toxoplasmosis is also of increasing concern in Alaska, especially for residents who practice subsistence hunting and gathering (KM 29.1).[56] In the eastern US, exposure to the amoeba (*Naegleria fowleri*) that causes primary amebic meningoencephalitis has been documented farther north.[57] Environmental fungal diseases like blastomycosis, coccidioidomycosis (Valley fever), cryptococcosis, and histoplasmosis are expected to be impacted by climate change.[58,59,60] Valley fever is expected to spread northward as drought and temperatures increase (KM 28.4). Case numbers are projected to increase by 220% by the end of the century under a very high scenario (RCP8.5).[61] Valley fever tends to afflict construction and agricultural workers,[62,63,64] and the disease disproportionately impacts Black and Latinx populations, possibly due to occupational exposure.[65,66,67,68]

Lyme disease and other tick-borne diseases account for approximately 80% of all reported cases of vector-borne diseases in the US[69,70] and have steadily increased over the last 20 years due to multiple factors, including climate change (Figure 24.8).[71,72,73] Increased distribution and abundance of ticks are projected to increase human disease cases.[74,75,76,77,78,79] Climate change has contributed to the expansion over the last 20–30 years of the Lone Star tick[80,81,82,83,84] and the Gulf Coast tick, which transmit multiple pathogens.[85] Climate change extends ticks' seasonal activity, prolonging human exposure.[76,86,87,88,89]

Mosquito-borne pathogen spread is influenced by weather, climate, and social factors.[90,91,92] Climate change alters the diversity and distribution of mosquito vectors of dengue, Zika, and chikungunya viruses.[93,94,95,96,97] Dengue is currently a risk in the contiguous US, the US Caribbean, Hawai'i, and US-affiliated Pacific Islands (KMs 23.1, 30.2).[98,99] Increasing weather variability (KM 4.1) may increase West Nile virus transmission. Regional West Nile virus projections indicate geographic expansion in the Northeast over the next 50 years due to climate-related changes in mosquito population distribution (KMs 22.2, 24.3).[100,101,102] Mosquito-borne transmission of other encephalitis viruses has been sporadic in the last decade and may increase as climate change extends seasonality and expands habitat suitability for mosquito species.[103,104,105,106,107,108,109,110,111]

### Regional Examples of Climate-Sensitive Infectious Diseases




**Some climate-sensitive infectious diseases are expected to see expanded geographic range and extended seasonality.**

**Figure 15.2.** The map shows select examples of regional climate-sensitive infectious diseases, based on recent changes in geographic range or incidence. Some regions will experience increases in tick- and mosquito-borne diseases, zoonotic diseases, and pathogens, both in geographic area and extended seasonality. Figure credit: Los Alamos National Laboratory, CDC, Columbia University, University of Arizona, and University of Colorado.

## *Food and Water*

Climate change negatively impacts water quality, water security, food security, and nutrition, which harms health, particularly for communities that rely on agriculture, fishing, and subsistence lifestyles (KMs 4.1, 11.2, 22.2, 23.1, 25.3). For example, the 2021 Pacific Northwest heatwave affected the livelihoods of farmers and Tribes by damaging crops and causing a die-off of mussels, clams, and oysters.[112]

The incidence of certain diseases caused by foodborne and waterborne pathogens is expected to increase due to climate conditions that promote bacterial growth and geographic spread. For instance, vibriosis is a disease caused by ingesting *Vibrio* bacteria in contaminated shellfish or water sources. Symptoms range from food poisoning–like illness to death. Climate change–related vibriosis cases are projected to increase by 51% by 2090 under an intermediate scenario (RCP4.5)[113] due to increasing *Vibrio* populations in warming waters, changing salinity, sea level rise–related coastal changes, and flooding (KM 9.1).[113,114,115,116,117]

## *Mental and Spiritual Health*

Extreme weather events, wildfires, and slow-onset disasters (e.g., drought, sea level rise) can contribute to adverse mental and spiritual health outcomes. These harms may arise from forced displacement and migration (KM 20.3), trauma, loss of sense of place and belonging, and disruption of livelihoods, lifeways, and social support systems.[118] Under-resourced communities bear greater mental and spiritual health burdens (KMs 22.2, 25.2, 27.5).

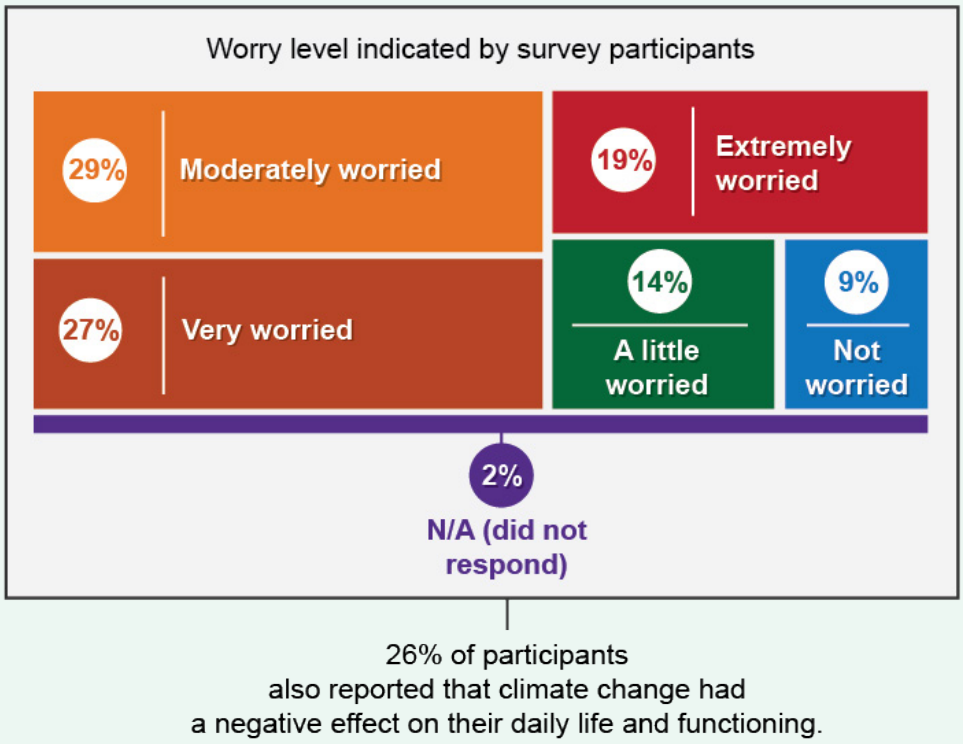
Mental health conditions including anxiety, depression, and suicide have become more prevalent in the US in the past decade, especially among adolescents.[119,120] Climate change may increase these mental health burdens.[55] Greater need for mental health services and psychiatric medications, as well as higher rates of anxiety, have been reported following major hurricanes (KM 23.1). For example, one in six mothers with low income experienced continued post-traumatic stress symptoms 12 years after Hurricane Katrina.[121,122,123,124] Many survivors of California's deadliest wildfire, the 2018 Camp Fire, experienced post-traumatic stress, depression, and anxiety[42] related to home loss and community disruption. Extreme heat exposure has been linked to worsening mental health, including suicide and interpersonal violence.[7,125]

Degradation or destruction of culturally significant places and flora and fauna relatives (KM 24.2),[126,127] shifts in timing of ceremonial practices, disruption of intergenerational teachings and sharing of knowledge and wisdom, and loss of place-based spirituality and traditional livelihoods and lifeways put spiritual health at risk, especially for Indigenous communities.[128,129]

## Box 15.1. Child and Adolescent Mental Health

Compared to previous generations, US children born in 2020 are more likely to experience climate-related adverse childhood events (ACEs) from damage to their homes, schools, and communities.[130] Children with four or more ACEs have 3- to 6-fold greater odds of having anxiety, depression, and substance use disorders and 30-fold greater odds of attempting suicide, in addition to greater physical health risks.[131] Concerns about a potentially uninhabitable world due to climate change can result in "eco-anxiety." Nearly 60% of 1,000 surveyed US adolescents reported anxiety about climate change, and nearly half believe that "humanity is doomed" (Figure 15.3),[132] despite evidence to the contrary (Chs. 1, 2, 31, 32). Psychological resilience training along with mental health care may lessen anxiety and promote engagement on climate change.[5,7,133,134] Youth climate education programs have focused on empowerment with the intent to reframe threats from climate change as opportunities to pursue solutions.[135,136]

### Children's Mental Health




**Out of 1,000 children and young people surveyed in the US, a majority expressed worry about climate change impacts to people and the planet.**

**Figure 15.3.** The figure shows the level of worry about climate change among young people ages 16–25. In the US, 46% of respondents said they were "very" or "extremely" worried about climate change, and 26% of respondents indicated that their feelings about climate change negatively affected their daily life and functioning, including at least one of the following: eating, concentrating, work, school, sleeping, spending time in nature, playing, having fun, and relationships.[132] Figure credit: Boston Children's Hospital, NOAA NCEI, and CISESS NC.

### *Compounding and Cascading Hazards*

Multiple climate-related extreme events that occur concurrently or in rapid succession (KM 2.3; Focus on Compound Events) can result in greater health impacts than singular events and limit the ability of individuals and communities to effectively prepare for, manage, and recover from these events. A singular event that cascades across multiple sectors or regions can result in compounded adverse health consequences. Examples include back-to-back heatwaves, heatwaves during wildfires, drinking-water contamination after flooding, and vector-control program breakdowns during and after flooding.[137] During 2005–2013, windstorms combined with power outages increased emergency department visits, hospital stays, and injury costs in New York, particularly for older individuals and Medicaid recipients.[138]

### *Occupational Safety and Health Impacts*

Climate-related increases in temperature are associated with increases in occupational injuries and occupational exposure to heat, potentially resulting in illness or death (KM 11.2).[139,140,141] Between 2011 and 2019, an average of 3,500 heat-related injuries, resulting in 38 fatalities per year, were reported to OSHA.[139] Between 2001 and 2018, higher-temperature days in California were associated with greatest increased risk of occupational injuries to men, lower-income workers, and young workers. Repeated heat stress coupled with dehydration in occupational environments is a risk factor for the development of kidney disease.[142] Extreme heat is expected to lead to lost labor hours, particularly for workers of color, individuals with low income, and those without a high school diploma. Additionally, these groups are more likely to live in areas where labor is most impacted by extreme heat.[143] Projected estimates of annual lost wages due to unsafe heat range from $19.2 billion to $46 billion (in 2022 dollars) by midcentury (under an intermediate scenario, RCP4.5).[144,145] Industries where workers experience increased risk of heat-related mortality include agriculture (KM 11.2), construction, transportation and warehousing, and waste management.[139] Workers can also face unsafe heat in indoor environments not equipped with adequate climate control.[139] Worker safety is also affected by climate change impacts on economic opportunity and wealth (KM 19.3), exposure to infectious diseases (Focus on COVID-19 and Climate Change), extreme events (Focus on Western Wildfires), and increased mental health risks.[146]

## Key Message 15.2

## Systemic Racism and Discrimination Exacerbate Climate Impacts on Human Health

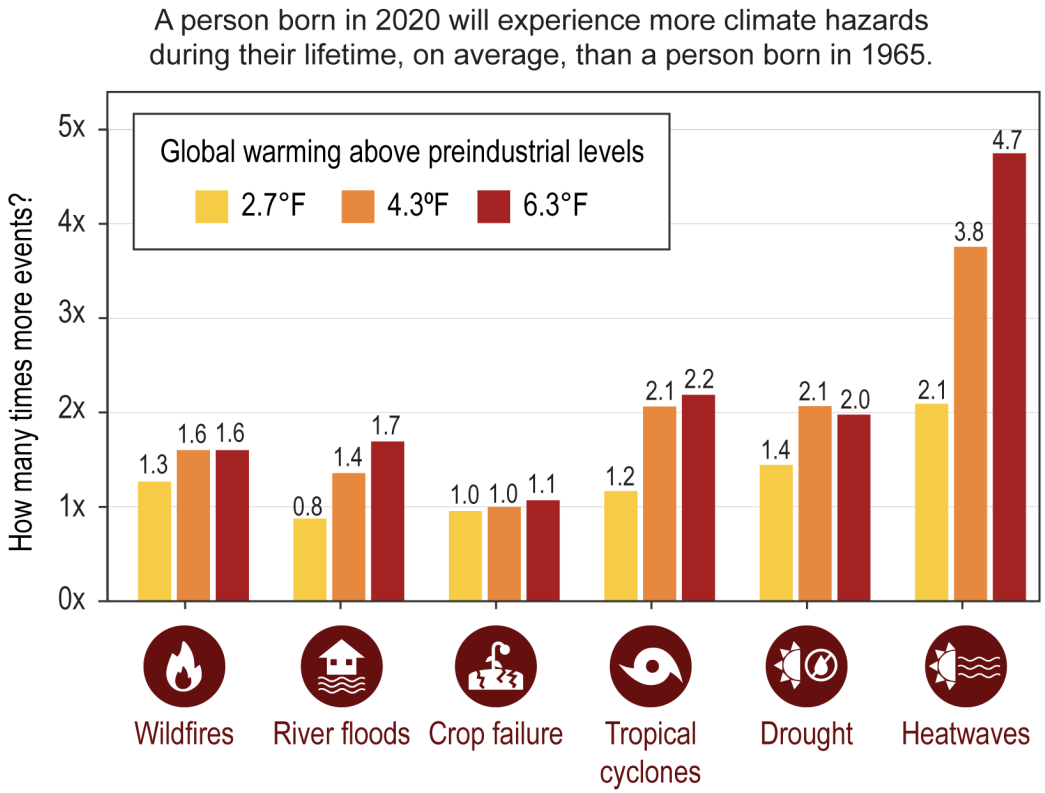
Climate change unequivocally worsens physical, mental, spiritual, and community health and well-being, as well as social inequities. It is an established fact that climate-related impacts disproportionately harm communities and people who have been marginalized. These include BIPOC (Black, Indigenous, and People of Color), individuals and communities with low wealth, women, people with disabilities or chronic diseases, sexual and gender minorities, and children.

### *Community Health and Health Equity*

Climate hazards negatively impact physical, mental, and community health.[147] Although extreme weather threatens all communities (Figure 15.3), health-related burdens are experienced more acutely by BIPOC and low-wealth communities that have been under-resourced and overburdened (KM 19.1; Figure 19.2).[143,148,149] Climate change creates intergenerational inequities as younger generations must endure more extreme

weather events than older ones (Figure 15.4). Valuation of intergenerational inequity can inform resilience and mitigation investments. Climate change is a threat multiplier, interacting with and magnifying other life-threatening stressors (Figure 15.5).[150] Fenceline communities—those located adjacent to hazardous industrial facilities, which are disproportionately BIPOC and low-wealth—face higher risks from chemical and industrial disasters following extreme weather.[151,152,153,154,155,156,157,158,159,160,161,162] Hazardous sites, threatened by flooding and sea level rise, exacerbate climate-related health inequities to BIPOC and communities with low wealth (KM 9.2).[163] Additionally, about 70% of Superfund sites—locations contaminated by hazardous materials designated for clean-up—are located within one mile of federally assisted housing, which disproportionately houses people of color, individuals with low wealth, and those with disabilities.[164]

### Intergenerational Inequity




**The number of climate hazards a person born in North America will experience during their lifetime depends on how much Earth warms above preindustrial levels.**

**Figure 15.4.** People born in North America in 2020, on average, will be exposed to more climate-related hazards compared to people born in 1965, an indication of intergenerational inequity. Figure credit: Boston Children's Hospital, NOAA NCEI, and CISESS NC.

## *Food and Water Systems*

Disruptions to food and water quality pose challenges to human health and disproportionately affect BIPOC communities, households with low wealth, single-parent households, and children (KM 11.2; Box 23.1).[165,166] In 2020, 10.5% of US households were food insecure, with higher rates reported among populations that have been marginalized.[165] There are growing concerns about aging or inadequate water infrastructure,[167] especially among households, including many in the Navajo Nation, who experience unequal access to piped and treated drinking water and who are dependent on hauling large quantities of water from nearby facilities.[168] Chemical, physical, and microbial contaminants (e.g., algal blooms and the toxins that cause

paralytic shellfish poisoning) threaten water supplies under drought conditions and high temperatures (KM 22.2), which is of particular concern among Indigenous populations who rely on subsistence fishing (KMs 10.1, 28.1, 29.1).

## Healthcare Access and Delivery

Climate-related extreme events have resulted in reductions in healthcare access and an increase in illness and death that can extend for months after the acute event, especially for communities with low wealth (KM 23.1).[169,170] Extreme events can disrupt care for chronic physical and mental health conditions. After hurricanes, risk of death among patients with lung cancer rises in proportion to the length of disaster declarations,[171] and delays in access to dialysis after Hurricane Sandy were associated with more emergency department visits and mortality among patients with chronic kidney disease.[172] Infrastructure and transportation failures contribute to poor health outcomes due to closures, lack of electricity or clean water sources, and/or road failures that prevent access to healthcare providers.[173]

## Tribal and Indigenous Peoples' Health

Tribal and Indigenous Peoples are disproportionately impacted by climate change, and they often equate the health of their people, culture, and traditional practices to the health of the environment (KMs 16.1, 29.1, 27.5, 30.2).[127,174,175] In addition to enduring the historical injustices of colonization, forced relocation, and land dispossession,[176] Indigenous Peoples are among the first to face the spiritual, physical, and mental health threats and impacts of climate change. This undermines their ability to maintain and access their cultural and economic lifeways and worsens community-wide vulnerabilities, such as limited water availability for use by humans, animals, and plants (KM 16.1).[129] Climate-related hazards such as flooding, erosion, sea level rise, and melting ice may lead to impassable roads in remote parts of Tribal territories, thereby widening gaps in the ability to access adequate healthcare (KM 29.2; Focus on Risks to Supply Chains).[177]

## Persons with Disabilities' Health

Climate change disproportionately and differentially harms the health of persons with disabilities, magnifies existing health and socioeconomic inequalities, creates unique challenges, and compounds disparities due to multiple discrimination.[178] During climate disasters, persons with disabilities are at heightened risk of mortality and injury, and they experience disruptions accessing assistive devices, medication, dialysis, other health services, and social support.[178,179] During periods of higher ambient temperatures and heatwaves, persons with physical and mental disabilities experience adverse health impacts, increased emergency room visits, and higher rates of mortality; cooling measures may be physically or financially inaccessible.[178,180] Persons with disabilities are also at elevated risk of exposure to chronic air pollution, as they disproportionately live in neighborhoods with heightened exposure to fine particulate matter due to lower wealth, higher unemployment, and undereducation relative to nondisabled peers.[181]

## African American and Latinx Peoples' Health

Climate change has had and will continue to have disproportionate adverse health impacts on communities with low wealth and BIPOC communities, worsening already-existing health disparities. Discriminatory policies and practices in housing, education, and siting of polluting facilities, including disinvestment in infrastructure and healthcare, amplify adverse climate-related health impacts (KM 22.2; Focus on Risks to Supply Chains).[150] Latinx populations, compared to other demographic groups, are 43% more likely to live in areas that will experience the highest labor reduction hours due to extreme high temperatures (with 2°C (3.6°F) of global warming by 2085–2095 compared to the 1986–2005 reference period).[143,145] African Americans are also expected to face disproportionately greater risks from climate change. African Americans and individuals with low income face higher risks of death from climate-driven floods and

air pollution compared to White people (Box 4.2).[143] People of color are disproportionately exposed to greenhouse gas co-pollutants like small particulate matter and face adverse health impacts as a result.[182,183] Due to housing discrimination and redlining, African Americans are more likely to live in neighborhoods with fewer trees and more pavement, suffer disproportionately from heat-related deaths, be exposed to worse air quality, and experience higher rates of asthma-related emergency room visits (KM 22.2; Figures 12.4, 12.6),[184,185,186,187] all of which are compounded by climate change. Latinx and other BIPOC communities face similar challenges (KM 14.3).[188,189]

## Women's Health

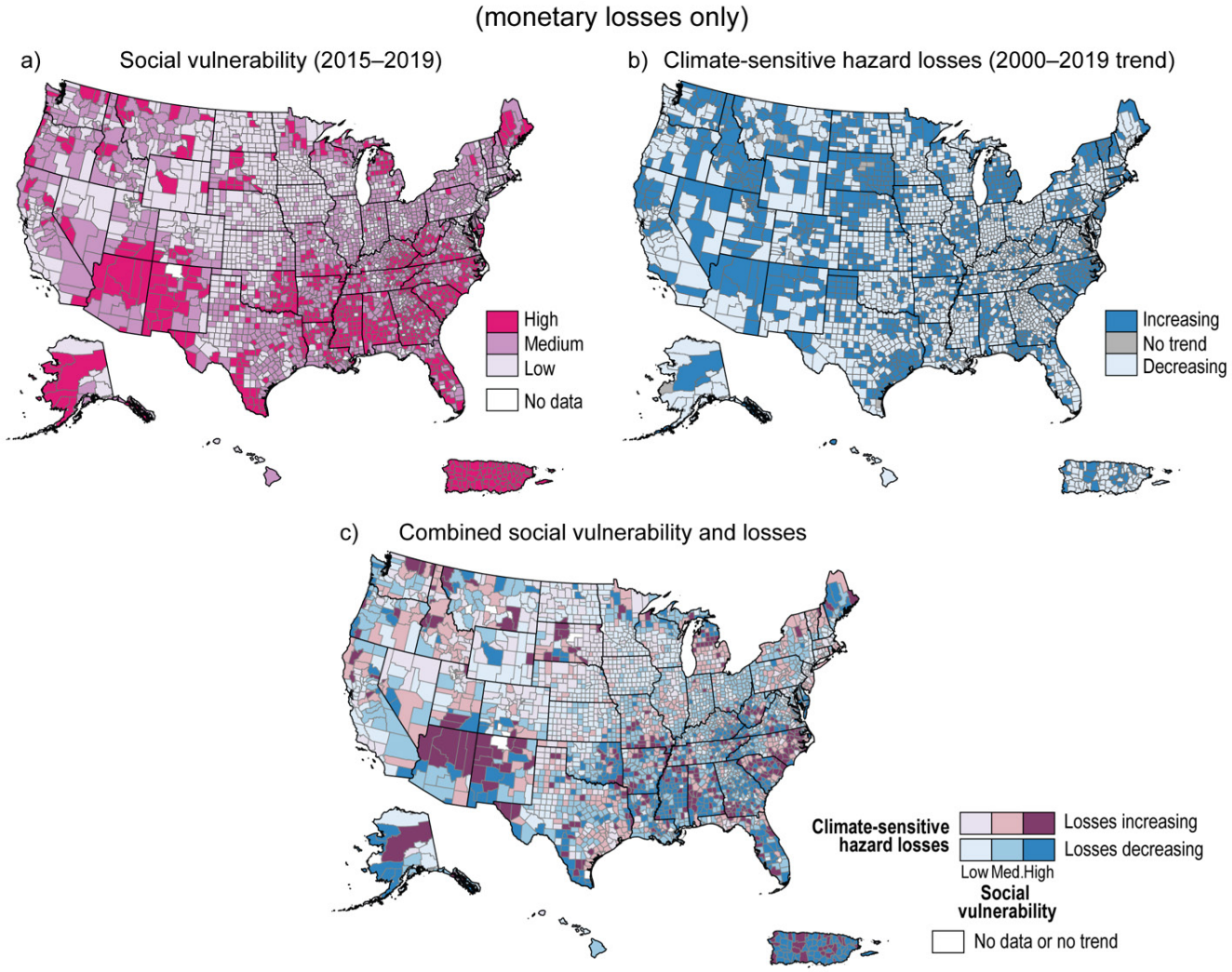
Women disproportionately experience the burden of climate change because of unique mental, sexual, and reproductive health needs that intersect with existing social, racial, and economic disparities. Women, and particularly women of color, are more likely to live in communities with low wealth,[190,191] which is associated with food insecurity[192] and exposure to particulate matter, extreme heat,[2] and climate-related disasters.[193,194] Pregnant cisgender women are particularly vulnerable because exposure to heat, particulate matter, and disaster-associated stressors leads to poor pregnancy outcomes, including miscarriages and low birth weight.[1,195] These factors contribute to maternal mortality, which is more prevalent in the US than in any other developed nation.[196] These outcomes are more likely in groups that have been marginalized, particularly Black pregnant people,[197,198] exacerbating existing social inequities.

In utero exposure to maternal stress during climate-related disasters is linked to subsequent psychiatric disorders in early childhood.[199] Additionally, women have higher caregiving burdens and decreased healthcare access, which makes recovering from climate-driven exposures more difficult. Transgender women may be required to stay in male-only shelters during climate-related disasters, negatively impacting their mental and physical health.[200,201]

## Sexual and Gender Minorities' Health

Sexual and gender minorities (SGMs) face social, economic, and health disparities and, as a result, experience greater risk of harm from climate change. SGMs are found in all populations, including frontline communities, and can experience compounding disparities and impacts on the basis of sexual orientation and gender identity. In 2015, Black and Latinx transgender individuals were more than three times as likely as the overall US population to be living below the poverty line (KMs 19.1, 23.1).[190] Indigenous SGMs face heightened health disparities as climate change continues to impact lifeways and economies.[202] SGMs may lack access to critical services during extreme events and are often not included in disaster preparedness and response plans due to discrimination and institutional structures that prioritize the needs of cisgender, heterosexual individuals;[200] may not recognize "chosen families"; and increasingly rely on faith-based organizations as first responders during disasters, which in some cases have blamed SGMs for devastating hurricanes and wildfires as a punishment from God.[193] These discriminatory beliefs have led some SGMs to not seek services at faith-based organizations for fear of being turned away or their SGM status being outed.[203] Because of religious bias, healthcare workers may also refuse to provide health services to or discriminate against SGMs during disasters.[204]

## Social Vulnerability and Climate Hazards




**Some highly vulnerable areas also have high economic losses from climate hazards.**

**Figure 15.5.** Panel (**a**) maps counties based on their Social Vulnerability Index (SoVI) scores for the period 2015–2019. SoVI uses 29 different inputs that characterize underlying socioeconomic and demographic factors, and the index is classified (high, medium, low) using standard deviations. Panel (**b**) shows counties with an increasing trend in climate-sensitive hazard losses (2000–2019) based on data from the Arizona State University/ASU Spatial Hazard Events and Losses Database for the US (SHELDUS). The data is based on property losses and excludes injuries and fatalities from climate-sensitive hazard losses. Exclusion of fatality (especially from heat) explains why some areas of the Southwest appear to have a seemingly decreasing loss trend. The composite map (**c**) identifies counties with high social vulnerability that have less capacity to prepare for, respond to, and rebound from increasing climate-related losses. SoVI does not fully capture the disproportionate impacts of climate hazards in specific neighborhoods, populations, and cultural groups within a county, nor does it account for risk created by historic marginalization. Figure credit: University of Central Florida, Arizona State University, NOAA NCEI, and CISESS NC.

## Key Message 15.3

## Timely, Effective, and Culturally Appropriate Adaptation and Mitigation Actions Protect Human Health

In every sector of society, implementing timely, effective, and culturally appropriate adaptation measures (*high confidence*), creating climate-resilient health systems (*high confidence*), and preventing the release of greenhouse gases can protect human health and improve health equity (*high confidence*).

### Risk Management and Integrated Approaches

Proactive and continuous risk management to protect at-risk groups and healthcare facilities is critical to human health and well-being (KM 31.3). This includes integrated approaches that mainstream health into food systems (KM 11.1), infrastructure, water, and sanitation policies. Mitigation options with significant health benefits include reducing point-source (e.g., coal-fired power plants) and mobile-source emissions, increasing active transport (e.g., walking), and increasing consumption of vegetables, legumes, fruits, and nuts (KMs 13.3, 32.4).[205] The economic value of avoided hospitalizations and premature deaths from mitigation activities is larger than the cost of implementation.[29]

### Climate-Resilient and Sustainable Health Systems

A climate-resilient health system can "anticipate, respond to, cope with, recover from, and adapt to" climate change to improve the health of communities (KMs 18.2, 19.2).[206,207] Focusing on equity, proactively addressing mental health needs, and linking to community health resources such as community health workers and long-term support and services can create a climate-resilient health system. Climate-related hazards routinely stress and disrupt healthcare systems and threaten access to healthcare for many. For example, a flooding event in 2019 damaged hospitals and disrupted access to healthcare across the central US.[208] Many hospitals (9.3%), nursing homes (10.2%), and pharmacies (12.1%) are at risk of flooding.[209] The COVID-19 pandemic exposed the lack of resilience of the healthcare system when confronted with a large, prolonged increase in healthcare needs (Focus on COVID-19 and Climate Change). Climate-sensitive health problems are linked to a significant economic burden on the healthcare system. There are numerous tools to identify threats and vulnerabilities to healthcare systems—such as the US Department of Health and Human Services' Sustainable and Climate Resilient Health Care Facilities Initiative—with frameworks to guide planning and implementation.[210]

Healthcare systems can play an important role in GHG reduction. The healthcare sector is responsible for 8.5% of US GHG emissions (Figure 19.5).[211,212] Transitioning to clean energy sources and introducing sustainable technologies into healthcare systems would reduce these emissions and associated health harms (KM 32.4).

### Benefits of Reducing Air Pollution

Air pollution is a leading cause of premature death worldwide (KM 14.1).[213] It has substantial impacts on lung, heart, and brain health; cancer; and mental health.[214] Reducing GHG emissions and human-caused air pollution would save lives and decrease the burden on the healthcare system (KMs 14.5, 32.4; Figure 32.15).

### Disease Surveillance

Implementing surveillance programs for climate-sensitive infectious diseases and non-infectious health outcomes (e.g., heat stroke, respiratory disease, mental and behavior health indicators) is an important

adaptation measure. The COVID-19 pandemic illustrated the need for modernization of the US surveillance system and the role of innovative surveillance strategies such as wastewater testing and community-based participatory surveillance (Focus on COVID-19 and Climate Change). Monitoring disease case counts, corresponding indicators (animal health and vector populations), and health outcomes facilitates identifying seasonal trends, responses to climate and environmental variability, geographic hotspots for diseases, and new or reemerging threats.[65,215,216] Enhanced disease surveillance identifies populations most at risk for contracting a disease and improves health by raising disease awareness and reducing time to diagnosis and treatment.[217] This increases capacity to plan for and prevent disease spread or outbreaks, such as by creating predictive models of disease transmission, implementing vector abatement programs, and developing and stockpiling vaccines and pharmaceuticals.[101,218,219,220]

## Extreme Heat

Increasing temperatures, urbanization, and an aging population (KM 2.2)[221,222] can result in increased heat-related deaths (KM 2.2).[221,222] Limiting warming to 1.5°C (2.7°F) above preindustrial levels (compared to 3°C, or 5.4°F) and timely adaptations could substantially decrease heat-related deaths, especially in cities.[223,224,225,226] Adaptations range from ensuring equitable access to cool spaces and reducing social isolation to augmenting heat warning systems and improving green infrastructure (KMs 12.3, 12.4).[224]

Air-conditioning access is limited for unhoused populations and households with low wealth. High electricity costs prevent effective use of air-conditioning.[227] Poor self-reported health and reduced life expectancy are more prevalent where families spend a large proportion of household income on residential energy.[228] Government programs can help families reduce their energy costs.[229] Home weatherization can improve health conditions and reduce healthcare costs while reducing GHG emissions, providing societal benefits greater than the implementation cost (KM 5.3).[230,231] There are self-reported health benefits from energy retrofits in households with low wealth.[232]

Increased air-conditioning use can exacerbate the urban heat island effect by transferring hot air from buildings to the outdoor environment (Ch. 12; Figure 12.4) and can increase electricity-related emissions of GHGs and other air pollutants.[233] Buildings that rely on air-conditioning may become dangerously hot during prolonged power outages.[234,235,236,237,238] Sustainable cooling strategies are in development, such as energy-efficient systems (e.g., heat pumps and fans) and affordable passive cooling (e.g., night-flush ventilation).[239,240,241,242]

## Wildfires

Under a range of future climate scenarios, wildfire pollutant emissions are expected to increase and result in significant health burdens.[243] Integrated wildfire management and adaptation strategies are critical to reducing deaths and illnesses, as wildfire risk cannot be eliminated. Proactive and effective management of fuel loads (e.g., through prescribed and cultural burning) can reduce wildfire size and intensity, but there may be unintended health consequences.[244] Strategies to reduce wildland fire smoke exposure include personal actions and community-level interventions (KM 14.2).[245] Early warning systems identify areas and populations experiencing higher smoke exposure on a near-real-time basis.[246,247]

## Vector-Borne Diseases

Climate change is a significant contributing factor to the increase in vector-borne disease cases reported over the last 20 years.[71,72,73] To adapt to these changing risks, new technologies to prevent transmission of vector-borne diseases are urgently needed, as traditional control measures, including insecticides, are rapidly becoming ineffective.[71,248,249,250] Recent advances include vaccines, spatial repellents, genetically

modified mosquitoes, and *Wolbachia* (a naturally occurring bacteria that reduces transmission of viruses such as dengue).

However, these novel adaptations are not yet operational due to funding, regulatory status, and infrastructure needs. Buy-in from communities and decision-makers is critical to ensure that emerging strategies can be utilized to protect health.[92,218,251,252,253,254] Coupling novel strategies with well-established community engagement practices, such as remediating vector habitat and increasing personal protective measures, can effectively reduce risk and empower communities.[255,256]

## Mental and Spiritual Health

Actions to support community social cohesion and cultural continuance, establish trusted and effective communication systems, and ensure that community members and/or officials can effectively manage disasters may buffer against adverse mental health outcomes.[147] A personal sense of agency to take climate action can reduce adverse mental health outcomes during extreme events. It can provide hope for survival and contribute to greater participation in community responses to climate change, which may also improve mental health resilience.[257]

## Community-Level Resilience and Adaptation Strategies to Build Capacity

Communities, connected through relationships and practices,[258] have unique priorities, traditions, and histories relevant to adaptation.[259] Many communities are already making proactive intergenerational adaptation decisions to reduce exposure to climate impacts, build capacity, and enhance healing and self-determination in the face of historical traumas (Figure 15.6).[260] Many Indigenous Peoples in the US practice cultural burning, a fire management approach that promotes ecosystem resilience and growth of culturally important medicinal plants[129,261] while also serving as an eco-centric adaptation strategy for improved planetary health.[262,263] The Swinomish Indian Tribal Community used values-driven data and community input in developing Indigenous health indicators and a climate change health assessment for adaptation decision-making; the indicators included community connection, self-determination, education, resilience, cultural use, and resource security.[174,264,265]

External adaptation strategies can exacerbate inequities through, for example, institutional racism, uneven distribution of adaptive capacity, and resource allocation that ignores distributive and historical injustices (KM 31.1). Adaptations (e.g., tree planting) that make an area more appealing for people with higher income could push existing residents out, resulting in eco-gentrification.[266,267] There are policies and institutional barriers to implementing whole-community adaptation actions.[129,268]

## Indigenous-Led Disaster Recovery Actions and Improved Health Outcomes

**Louisiana Tribal leaders are upholding sovereignty and self-determination in their climate adaptation actions following hurricane damage.**

**Figure 15.6.** Tribal leaders from coastal Louisiana shared Indigenous and local knowledge, wisdom, and experiences of the health impacts and resilience-building recovery actions following Hurricane Ida, which made landfall in coastal Louisiana in August 2021. Interviews were recorded during a convening where the Tribal leaders came together to share how Louisiana Tribes are adapting to climate change while upholding sovereignty and working to improve health outcomes. Link to videos. Image credit: ©Craig Richard and Unitarian Universalist Service Committee, in collaboration with the First People's Conservation Council of Louisiana, Lowlander Center, Livelihoods Knowledge Exchange Network, and Disaster Justice Network, July 2022.

Addressing immediate needs and developing healthier long-term outcomes that reduce inequities[269] and strengthen community resilience[147] involves collaboration and cooperation across multiple scales. Persons with disabilities, for example, are often excluded from adaptation and mitigation efforts,[270] and there is a strong need for disability-inclusive climate planning and response.[271] The most impacted communities must be included in decision-making, from visioning and planning through implementation.[258,272,273]

Community adaptation capacity is enhanced by building and sharing flexibility, humanity, spirituality, and resilience. To be effective, adaptation strategies must integrate workforce development into co-governance and promote institutional support systems for community-defined, -driven, and -led adaptation efforts that include a diversity of cultures, histories, lifeways, and knowledge systems.[129,260,274]

# Traceable Accounts

## *Process Description*

Chapter authors were selected over a three-week period in August 2021. The initial discussion centered around authors who had been nominated or who had self-nominated. The chapter lead author and federal coordinating lead author then expanded the list and focused on balancing career stage, topic expertise, geographic location, and type of institution (academic, federal government, nonprofit). Once the chapter lead author had narrowed down the search, the authors were contacted. All contacted authors agreed to participate and were invited to complete the survey to be officially enrolled. The 18 authors for the Human Health chapter are subject experts in the topics selected for inclusion. Technical contributors were added as needed during the response to comments from the public and the National Academies to bring in additional data and subject-matter expertise.

Authors reviewed and evaluated scientific literature on the human health impacts of climate change, with a focus on new and emerging evidence since the Fourth National Climate Assessment (NCA4). Authors also reviewed technical inputs (submitted as part of the NCA5 process) for relevant information. The entire author team regularly met virtually to create and review chapter content; all authors participated in determining Key Messages and chapter topics and content. A public engagement workshop was held to solicit public input. The chapter was informed by workshop participants' concerns and comments. Authors also met in person in April 2023 to continue writing and incorporating additional information in response to review comments.

## Key Message 15.1

## Climate Change Is Harming Human Health

### Description of Evidence Base

Multiple lines of evidence demonstrate that climate change is already harming human health.[69,269,275,276] Evidence indicates that extreme events and climate-related environmental changes will continue to place stress on food, water, and energy supplies (KM 2.2). This, in turn, will negatively impact the health of the US population in many ways, including reduced access to healthcare. Based on recent peer-reviewed research, this Key Message outlined the existing health impacts in the areas of extreme heat, drought, wildfires, infectious diseases, food and water quality and security, mental and spiritual health, compounding hazards, and occupational safety. Studies demonstrate that these trends will continue to increase.[269,277]

Evolving attribution science allows researchers to study how extreme events, and resultant health impacts, were influenced by climate change. This growing evidence line contributes to our understanding of the role of climate change in the health impacts of heatwaves, floods, droughts, and other disasters.[278,279,280,281]

### Major Uncertainties and Research Gaps

While ample evidence demonstrates the health impacts of climate change, uncertainties remain on specific aspects of these impacts. For example, uncertainties in projections of human health outcomes in response to climate change can partially stem from the underlying human case data involved in the research, which is subject to underreporting or underdiagnosing the human case counts. Quantifying the impacts of climate change on human health is challenging due to lack of long-term surveillance and datasets; differential exposures based on location; and underlying health inequities.[282] In addition, health surveillance related to extreme weather is being improved through utilization of syndromic ("real-time") surveillance, data mod-

ernization initiatives, and integration of existing surveillance systems. Decades of research on the impacts of climate change on infectious disease illustrate the complexity of the pathways by which climate change may alter disease transmission dynamics. Uncertainties arise from geographic differences in social–behavioral–environmental interactions, vector and non-human reservoir species involved in the disease system, and difficulties in isolating the impact of climate change from other significant environmental and human-driven changes (App. 4.6).

Evidence is growing that there are emerging mosquito-borne diseases and species that are able to transmit pathogens in the US. However, not all of these are linked entirely to climate change but also to land-use change, global trade, and importation of pathogens related to travel.

There is also a growing body of evidence exploring the bionomics of mosquitoes and ticks and the pathogens they carry to better understand the underlying mechanisms by which changes in thermal conditions could increase or decrease disease risk.[283]

Most projection models of range do not use disease but rather vector range as the endpoint. Arizona, for example, has an abundance of the dengue virus vector *Aedes aegypti*, but there has been little documentation of local transmission of dengue.[284,285] There is also uncertainty around how the mosquitoes and ticks themselves, as well as the pathogens they are carrying, will adapt to climate change.[76]

Uncertainty also stems from challenges with surveillance systems and data collection relating to heat injury and illness, especially in the occupational setting. As is the case with occupational data generally, data on and estimates of heat-related morbidity and mortality differ based on the source of the data.[286,287] Some heat-related impacts may not be properly categorized as heat-related[288] and may not accurately capture the location of exposure, as it may be reported either by the person's residence or by the location where medical treatment was sought.[289] Further, the Bureau of Labor Statistics estimates that its accounting of occupational injuries and illness are undercounted.[290,291] It is therefore challenging to estimate the true number of injuries and illnesses due to extreme heat, and heat morbidity and mortality are underreported.[139] Occupational health impacts from other climate hazards may also be underreported.

Recent cold spells in Texas (e.g., February 2021) and other regions have highlighted the impacts of cold weather on communities, including fatalities that resulted from cold weather exposure and power failures.[292,293] Whether such trends in cold spells will continue is uncertain,[294] but colder temperatures are associated with adverse health outcomes and increase the risks of death and illness.[295,296,297] Positive and negative health impacts arising from climate-related shifts in ice storms, blizzards, and cold spells are an area for future research.

There is little research on the long-term health impacts of wildfire smoke exposure in communities that face repeated wildfires or on human health harms, and associated costs, from exposure to compounding and cascading hazards. There is a lack of research exploring the pathways associated with drought and human health in the United States. The full range of mental health impacts of climate change and climate-related events is not yet fully understood.[298] Additional research is needed in all of these areas, including compounding events such as drought and flooding, to better describe the pathways that affect human health.

There are important administrative, logistical, and methodological challenges in assessing mortality and morbidity common to large-scale disasters and public health emergencies of any provenance. These challenges undercut the ability of practitioners to gather, report, and use mortality and morbidity data to save lives and protect health in the wake of a public health event, from the initial devastation through the long tail of recovery. Accurate and timely information about mortality and significant morbidity related to the disaster is the cornerstone of the efforts of the disaster management enterprise and will require holistic

data systems and new approaches in order to be more effective.[299] Specifically, there is not a standardized methodology for counting excess deaths during and after hurricanes, which can result in an underestimation of number of deaths (Figure 23.5).[300] Similarly, vector-borne, food-borne, and water-borne diseases are not fully captured in case numbers.[71,301] For example, cases of the rare, and typically fatal, primary amebic meningoencephalitis from exposure to the amoeba *Naegleria fowleri* have been documented farther north, although this conclusion is based on limited case numbers.[57] Thus, the true burden of climate-attributable health effects may not be known; more research is needed to quantify health impacts in relation to physical, mental, and spiritual health.

### Description of Confidence and Likelihood

Based on multiple lines of peer-reviewed evidence, including field studies, laboratory studies, model projections, and systematic reviews, it is an established fact that climate change is negatively impacting the health of the US population. Based on the amount and quality of peer-reviewed research, it is *very likely*, with *very high confidence*, that climate-related hazards will continue to grow, increasing human health impacts across all regions of the United States. Adaptation and mitigation activities could reduce this impact and protect health; the scope and scale of these efforts will determine future confidence levels around health impacts.

## Key Message 15.2

## Systemic Racism and Discrimination Exacerbate Climate Impacts on Human Health

### Description of Evidence Base

While all people in the US face health risks linked to climate change, some populations are affected sooner and more intensely.[269,302] This is because of differences in the number of and severity of exposures to climate hazards (Figure 15.5), sensitivity to these hazards, and ability to adapt (KM 20.3).[99] This Key Message outlines how ample peer-reviewed literature and data indicate that some populations disproportionately face environmental injustices, including impacts from climate-related extreme events. Systemic racism, discriminatory policies, and longstanding marginalization and disenfranchisement all contribute to increased climate vulnerability and to determining who bears the most climate risk.[99,303] Specifically, this Key Message outlines the peer-reviewed evidence behind climate change's disproportionate impact in the areas of community health, food and water systems, healthcare access and delivery, Tribal and Indigenous Peoples' health, persons with disabilities' health, African American and Latinx peoples' health, women's health, and sexual and gender minorities' health.

### Major Uncertainties and Research Gaps

There is relatively little community-driven participatory research on the health impacts of climate change, which leads to a lack of full understanding of impacts on disproportionately at-risk populations. There may also be underreporting of health outcomes due to a lack of healthcare access in some communities. For example, the mechanisms causing certain demographics, such as Black and Latinx populations, to have an increased risk of contracting Valley fever are unknown. More research is needed to determine links among higher rates of occupational exposure, societal factors such as access to healthcare or health insurance, or genetics.[68]

There is limited data on well-water usage and quality in some states, and limited funding and capacity for water quality testing in disproportionately impacted communities.[304] Similarly, there is a research gap on

aspects of climate change impacts on food quality, security, and nutrition in the US, as much of the research focuses on developing countries.[305,306]

There is also limited research on system-wide health impacts, in which communities, ecosystems, and all living relatives depend on the holistic, intact system to survive and thrive.[307] Such understanding is important to ensure that adaptation does not happen in silos or isolation but rather includes the entire living system and that the proposed actions can actually achieve the intended results; this can determine the ability not only to survive but also thrive for generations to come. This is of particular importance to Indigenous communities.

More research could increase understanding of gender disparities for women and for sexual and gender minorities.[193] More research on risk factors and contextualized vulnerabilities could also provide better insights into acceptable prevention and control strategies that can be implemented to protect the health of disproportionately impacted populations. There is limited research exploring the unique vulnerabilities of women and gender minorities in pregnancy, as well as the impact on fetal outcomes.[1,308,309] Some studies demonstrate that women experience more significant health consequences, but very few directly relate them to climate change specifically.[197]

Research gaps at the intersection of disability, climate change, and health are impeding the development of effectual climate adaptation and mitigation policies and initiatives.[271,310] Participatory research is required to understand the climate impacts and health disparities experienced by the heterogeneous disability community.[271] Future climate-related health research can consider compounding multiple discrimination, including persons with disabilities, African Americans, Latinx, women, children, Indigenous People, older persons, and sexual and gender minorities.[178,271,310] A bottom-up approach to the development of public health responses with and by organizations of persons with disabilities may advance innovative public health approaches.[271] Additional research on the health effect of heat could demonstrate effectiveness of interventions for the diverse disability community.[271] Moreover, further environmental justice research inclusive of persons with physical and mental disabilities would assist climate adaptation and mitigation planning and initiatives.[311] A greater proportion of persons with ambulatory and cognitive disabilities were found to reside in neighborhoods with Hurricane Harvey–induced flooding in Harris County, Texas, many in public housing in non-White neighborhoods with low wealth; such research is vital to future disaster risk-reduction strategies.[312] Accurate health surveillance of morbidity and mortality among disability populations that have been marginalized, including persons with intellectual disabilities, is critical to ensuring disability-inclusive climate responses.[271] Additional research would improve knowledge of climate and health impacts on the Latinx population. The use of the term Latinx in the chapter is used to reflect gender diversity and is inclusive of nonbinary, gender nonconforming, and transgender individuals. The term Latinx is primarily used by younger generations and sexual and gender minorities.[313] Some literature suggests that the term should not be used because *x* is not common in the Spanish language, upholds a Western idea that gender neutrality is grammatically superior, and, when used to refer to all Latinx individuals, can erase Latinas similar to the way that "Latinos" does.[313,314,315] Other literature suggests that use of the term allows for individuals, who are often erased and discriminated against, to self-identify as a gender outside of or between the binary or who may not have a gender at all.[313] Use in this chapter is consistent with the inclusion of the sexual and gender minorities section and the CDC's adoption of the term "Latinx" when referring to health equity.[99] Additional community-based research to inform specific impacts on Latinx communities is needed.

There is limited data at the census tract level or similar geographic scale on social vulnerability and climate hazards. Figure 15.5 identifies specific counties with increasing trends in climate hazard–related economic loss that also are designated as vulnerable using the SoVI (Social Vulnerability Index), which synthesizes information across multiple variables at the county scale. It does not, however, fully capture the dispropor-

tionate impacts of climate hazards in specific neighborhoods or on specific population or cultural groups within a county, nor does it account for risk created by historic marginalization.

Furthermore, data suppression due to health privacy concerns can limit the availability of data for research on specific racial or gender groups. In addition, political sensitivities around the topic of climate change impacts on specific populations can hinder research and response.

### Description of Confidence and Likelihood

It is unequivocal that some populations are already disproportionately impacted by climate change, as evidenced by multiple lines of data and peer-reviewed research that included longitudinal field studies. Research and data indicate that disproportionately affected populations include persons with disabilities, older adults, pregnant people, children, sexual and gender minorities, some communities of color, and those living in communities that have been under-resourced and over-burdened. Populations at higher risk will continue to be negatively impacted by climate change unless disparities are addressed and adaptation and mitigation strategies are targeted to benefit all communities and, in particular, those that have been marginalized.

## Key Message 15.3

## Timely, Effective, and Culturally Appropriate Adaptation and Mitigation Actions Protect Human Health

### Description of Evidence Base

Multiple lines of research indicate that the health of the US population benefits from adaptation and mitigation activities, including integrated approaches to mainstream health into policies such as improvements in food, infrastructure, water, and sanitation. There is growing evidence that various adaptive strategies (e.g., cooling centers, building resilient healthcare infrastructure, communication campaigns, etc.) have an impact on knowledge, attitudes, and behaviors that can improve health.[269,316] For example, federal programs from the US Department of Health and Human Services (Low Income Home Energy Assistance Program) and the Department of Energy (Weatherization Assistance Program), as well as state governments, are implementing a suite of additional energy efficiency programs to help families reduce their energy costs and protect their health.[229] Recent research and limited literature reviews describe and classify the level of effectiveness of various adaptations and interventions to protect health.[316,317,318] This evidence informed the Key Message content related to adaptation. Additional research and evidence showing direct impact on human health outcomes would be needed to increase the confidence level to *very high*.

Peer-reviewed evidence indicates that strategies to reduce greenhouse gas emissions (mitigation) can protect health by reducing future climate hazards.[205] They also can increase resilience by providing co-benefits that immediately improve health.[319] The economic value of avoided hospitalizations and premature deaths are of the same order of magnitude as or larger than the cost of implementing the mitigation polices.[29]

### Major Uncertainties and Research Gaps

There are still uncertainties and research gaps around timely, effective, and culturally appropriate adaptation and mitigation actions, including in the areas of risk management and integrated approaches, community-level resilience and adaptation strategies to build capacity, climate resilient and sustainable health systems, benefits of reducing air pollution, disease surveillance, and actions to protect populations from extreme heat, wildfires, and vector-borne diseases.

Further research could help document the effectiveness of adaptation and mitigation options in both the short term and long term. This could include examining the specifics affecting the success of interventions, including enabling conditions, constraints, and barriers, as well as effective approaches to overcome challenges and to scale up effective measures. Some mitigation and adaptation activities can have unintended negative health consequences; for example, trees planted to provide shade and reduce exposure to unsafe temperatures may inadvertently increase pollen levels and pose a hazard to those with respiratory health issues such as asthma.[320,321] Providing timely pollen information to clinicians, public health practitioners, and the public could increase awareness and allow at-risk individuals to take preventive measures (KM 14.4). Because pollen monitoring stations are sparsely distributed, using nontraditional data sources such as information from web searches[322] and near-real-time data on symptoms of emergency department patients[323] can offer alternative ways of gathering and communicating potential risks of pollen exposure.

There is also a lack of research on the effectiveness of some health-protective actions in different regions and among varying population demographics; for example, tree planting may not be a feasible strategy to provide shade in a water-scarce ecosystems such as the desert Southwest. More research would improve understanding on how individual and community-level social capital impacts the effectiveness of adaptation and mitigation strategies.[324] More research would also help tailor health communication messages to specific populations, an effective strategy to protect health.[325]

Continuous improvements in research and modeling can help drive evidence-based public health responses to minimize illness and death.[224,225,226] Climate-sensitive disease or health-outcome surveillance systems could be integrated with weather event tracking and economic cost estimates to assess the overall impact of such events.[31,326]

There is limited curriculum on the health impacts of climate change. Greater integration into medical school, nursing school, and public health curricula can increase awareness of the established links between climate change and health and effective adaptation and mitigation strategies to reduce these health impacts.[327,328]

Health departments are chronically underfunded, and most do not have the resources to prepare for and respond to the health impacts of climate change.[329] Increased capacity is needed to track hazards, build community resilience, and address cascading hazards. Improved data and capacity would allow for more effective adaptation and mitigation actions to protect health. Healthcare and public health worker shortages and unstable funding limit the ability of practitioners to engage in climate change–related health protection activities.

More research is also needed on community acceptability of adaptation and mitigation interventions to ensure effectiveness and sustainability. In addition, there are still gaps in implementation science ("the scientific study of methods and strategies that facilitate the uptake of evidence-based practice and research into regular use by practitioners and policymakers"[330]), a practice that helps ensure interventions benefit the communities that are most impacted by climate change.[99]

## Description of Confidence and Likelihood

In the first statement of Key Message 15.3, the author team determined that there is *high confidence* that human health can be protected if adaptation measures are implemented. This statement is based on multiple lines of peer-reviewed evidence and real-world examples of successful adaptation strategies. Measures such as building energy retrofits, the establishment of education and outreach programs, installation of white roofs, and improvement of equitable access to cooling centers and green spaces can help protect human health if the necessary resources to implement these strategies exist or are made available. Based on peer-reviewed literature, there is also *high confidence* that creating climate-resilient health

systems will protect health and *high confidence* that mitigation efforts to reduce greenhouse gas emissions can protect health and improve health equity.

There is some uncertainty because it is difficult to determine future human behavioral response to the proposed adoption of adaptation and mitigation strategies. In order to improve health equity, it remains important to contextualize these strategies to specific communities, determine acceptability of strategies to specific communities prior to introduction, and investigate potential unintended consequences prior to adoption of mitigation strategies.

# References


1. Bekkar, B., S. Pacheco, R. Basu, and N. DeNicola, 2020: Association of air pollution and heat exposure with preterm birth, low birth weight, and stillbirth in the US: A systematic review. *JAMA Network Open*, **3** (6), e208243. https://doi.org/10.1001/jamanetworkopen.2020.8243

2. Chersich, M.F., M.D. Pham, A. Areal, M.M. Haghighi, A. Manyuchi, C.P. Swift, B. Wernecke, M. Robinson, R. Hetem, M. Boeckmann, and S. Hajat, 2020: Associations between high temperatures in pregnancy and risk of preterm birth, low birth weight, and stillbirths: Systematic review and meta-analysis. *BMJ*, **371**, m3811. https://doi.org/10.1136/bmj.m3811

3. Malley, C.S., D.K. Henze, J.C.I. Kuylenstierna, H.W. Vallack, Y. Davila, S.C. Anenberg, M.C. Turner, and M.R. Ashmore, 2017: Updated global estimates of respiratory mortality in adults ≥30years of age attributable to long-term ozone exposure. *Environmental Health Perspectives*, **125** (8), 087021. https://doi.org/10.1289/ehp1390

4. Obradovich, N., R. Migliorini, M.P. Paulus, and I. Rahwan, 2018: Empirical evidence of mental health risks posed by climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (43), 10953–10958. https://doi.org/10.1073/pnas.1801528115

5. Palinkas, L.A. and M. Wong, 2020: Global climate change and mental health. *Current Opinion in Psychology*, **32**, 12–16. https://doi.org/10.1016/j.copsyc.2019.06.023

6. Peters, A. and A. Schneider, 2021: Cardiovascular risks of climate change. *Nature Reviews Cardiology*, **18** (1), 1–2. https://doi.org/10.1038/s41569-020-00473-5

7. Thompson, R., R. Hornigold, L. Page, and T. Waite, 2018: Associations between high ambient temperatures and heat waves with mental health outcomes: A systematic review. *Public Health*, **161**, 171–191. https://doi.org/10.1016/j.puhe.2018.06.008

8. Bailey, Z.D., J.M. Feldman, and M.T. Bassett, 2021: How structural racism works—racist policies as a root cause of US racial health inequities. *New England Journal of Medicine*, **384** (8), 768–773. https://doi.org/10.1056/nejmms2025396

9. Ebi, K.L., J. Vanos, J.W. Baldwin, J.E. Bell, D.M. Hondula, N.A. Errett, K. Hayes, C.E. Reid, S. Saha, J. Spector, and P. Berry, 2021: Extreme weather and climate change: Population health and health system implications. *Annual Review of Public Health*, **42** (1), 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

10. McDermott-Levy, R., M. Scolio, K.M. Shakya, and C.H. Moore, 2021: Factors that influence climate change-related mortality in the United States: An integrative review. *International Journal of Environmental Research and Public Health*, **18** (15), 8220. https://doi.org/10.3390/ijerph18158220

11. Woolf, S.H., H. Schoomaker, L. Hill, and C.M. Orndahl, 2019: The social determinants of health and the decline in U.S. life expectancy: Implications for Appalachia. *Journal of Appalachian Health*, **1** (1), 6–14. https://doi.org/10.13023/jah.0101.02

12. Vicedo-Cabrera, A.M., N. Scovronick, F. Sera, D. Royé, R. Schneider, A. Tobias, C. Astrom, Y. Guo, Y. Honda, D.M. Hondula, R. Abrutzky, S. Tong, M.d.S.Z.S. Coelho, P.H.N. Saldiva, E. Lavigne, P.M. Correa, N.V. Ortega, H. Kan, S. Osorio, J. Kyselý, A. Urban, H. Orru, E. Indermitte, J.J.K. Jaakkola, N. Ryti, M. Pascal, A. Schneider, K. Katsouyanni, E. Samoli, F. Mayvaneh, A. Entezari, P. Goodman, A. Zeka, P. Michelozzi, F. de'Donato, M. Hashizume, B. Alahmad, M.H. Diaz, C.D.L.C. Valencia, A. Overcenco, D. Houthuijs, C. Ameling, S. Rao, F. Di Ruscio, G. Carrasco-Escobar, X. Seposo, S. Silva, J. Madureira, I.H. Holobaca, S. Fratianni, F. Acquaotta, H. Kim, W. Lee, C. Iniguez, B. Forsberg, M.S. Ragettli, Y.L.L. Guo, B.Y. Chen, S. Li, B. Armstrong, A. Aleman, A. Zanobetti, J. Schwartz, T.N. Dang, D.V. Dung, N. Gillett, A. Haines, M. Mengel, V. Huber, and A. Gasparrini, 2021: The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, **11** (6), 492–500. https://doi.org/10.1038/s41558-021-01058-x

13. Ebi, K.L., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, and O. Jay, 2021: Hot weather and heat extremes: Health risks. *The Lancet*, **398** (10301), 698–708. https://doi.org/10.1016/s0140-6736(21)01208-3

14. Thomas, N., S.T. Ebelt, A.J. Newman, N. Scovronick, R.R. D'Souza, S.E. Moss, J.L. Warren, M.J. Strickland, L.A. Darrow, and H.H. Chang, 2021: Time-series analysis of daily ambient temperature and emergency department visits in five US cities with a comparison of exposure metrics derived from 1-km meteorology products. *Environmental Health*, **20** (1), 55. https://doi.org/10.1186/s12940-021-00735-w

15. Vaidyanathan, A., S. Saha, A.M. Vicedo-Cabrera, A. Gasparrini, N. Abdurehman, R. Jordan, M. Hawkins, J. Hess, and A. Elixhauser, 2019: Assessment of extreme heat and hospitalizations to inform early warning systems. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (12), 5420–5427. https://doi.org/10.1073/pnas.1806393116

16. Bernstein, A.S., S. Sun, K.R. Weinberger, K.R. Spangler, P.E. Sheffield, and G.A. Wellenius, 2022: Warm season and emergency department visits to U.S. children's hospitals. *Environmental Health Perspectives*, **130** (1), 017001. https://doi.org/10.1289/ehp8083

17. Meade, R.D., A.P. Akerman, S.R. Notley, R. McGinn, P. Poirier, P. Gosselin, and G.P. Kenny, 2020: Physiological factors characterizing heat-vulnerable older adults: A narrative review. *Environment International*, **144**, 105909. https://doi.org/10.1016/j.envint.2020.105909

18. Nori-Sarma, A., S. Sun, Y. Sun, K.R. Spangler, R. Oblath, S. Galea, J.L. Gradus, and G.A. Wellenius, 2022: Association between ambient heat and risk of emergency department visits for mental health among US adults, 2010 to 2019. *JAMA Psychiatry*, **79** (4), 341–349. https://doi.org/10.1001/jamapsychiatry.2021.4369

19. O'Lenick, C.R., A. Baniassadi, R. Michael, A. Monaghan, J. Boehnert, X. Yu, M.H. Hayden, C. Wiedinmyer, K. Zhang, P.J. Crank, J. Heusinger, P. Hoel, D.J. Sailor, and O.V. Wilhelmi, 2020: A case-crossover analysis of indoor heat exposure on mortality and hospitalizations among the elderly in Houston, Texas. *Environmental Health Perspectives*, **128** (12), 127007. https://doi.org/10.1289/ehp6340

20. Benz, S.A. and J.A. Burney, 2021: Widespread race and class disparities in surface urban heat extremes across the United States. *Earth's Future*, **9** (7), e2021EF002016. https://doi.org/10.1029/2021ef002016

21. Tuholske, C., K. Caylor, C. Funk, A. Verdin, S. Sweeney, K. Grace, P. Peterson, and T. Evans, 2021: Global urban population exposure to extreme heat. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (41), e2024792118. https://doi.org/10.1073/pnas.2024792118

22. Wilson, B., 2020: Urban heat management and the legacy of redlining. *Journal of the American Planning Association*, **86** (4), 443–457. https://doi.org/10.1080/01944363.2020.1759127

23. Hass, A.L., J.D. Runkle, and M.M. Sugg, 2021: The driving influences of human perception to extreme heat: A scoping review. *Environmental Research*, **197**, 111173. https://doi.org/10.1016/j.envres.2021.111173

24. Howe, P.D., J.R. Marlon, X. Wang, and A. Leiserowitz, 2019: Public perceptions of the health risks of extreme heat across US states, counties, and neighborhoods. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (14), 6743–6748. https://doi.org/10.1073/pnas.1813145116

25. Madrigano, J., K. Lane, N. Petrovic, M. Ahmed, M. Blum, and T. Matte, 2018: Awareness, risk perception, and protective behaviors for extreme heat and climate change in New York City. *International Journal of Environmental Research and Public Health*, **15** (7), 1433. https://doi.org/10.3390/ijerph15071433

26. Jacobsen, A.P., Y.C. Khiew, E. Duffy, J. O'Connell, E. Brown, P.G. Auwaerter, R.S. Blumenthal, B.S. Schwartz, and J.W. McEvoy, 2022: Climate change and the prevention of cardiovascular disease. *American Journal of Preventive Cardiology*, **12**, 100391. https://doi.org/10.1016/j.ajpc.2022.100391

27. Martin-Latry, K., M.P. Goumy, P. Latry, C. Gabinski, B. Bégaud, I. Faure, and H. Verdoux, 2007: Psychotropic drugs use and risk of heat-related hospitalisation. *European Psychiatry*, **22** (6), 335–338. https://doi.org/10.1016/j.eurpsy.2007.03.007

28. Puvvula, J., A.M. Abadi, K.C. Conlon, J.J. Rennie, S.C. Herring, L. Thie, M.J. Rudolph, R. Owen, and J.E. Bell, 2022: Estimating the burden of heat-related illness morbidity attributable to anthropogenic climate change in North Carolina. *GeoHealth*, **6** (11), e2022GH000636. https://doi.org/10.1029/2022gh000636

29. Shindell, D., M. Ru, Y. Zhang, K. Seltzer, G. Faluvegi, L. Nazarenko, G.A. Schmidt, L. Parsons, A. Challapalli, L. Yang, and A. Glick, 2021: Temporal and spatial distribution of health, labor, and crop benefits of climate change mitigation in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (46), e2104061118. https://doi.org/10.1073/pnas.2104061118

30. NCEI, 2022: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

31. Limaye, V.S., W. Max, J. Constible, and K. Knowlton, 2019: Estimating the health-related costs of 10 climate-sensitive U.S. events during 2012. *GeoHealth*, **3** (9), 245–265. https://doi.org/10.1029/2019gh000202

32. Abadi, A.M., Y. Gwon, M.O. Gribble, J.D. Berman, R. Bilotta, M. Hobbins, and J.E. Bell, 2022: Drought and all-cause mortality in Nebraska from 1980 to 2014: Time-series analyses by age, sex, race, urbanicity and drought severity. *Science of The Total Environment*, **840**, 156660. https://doi.org/10.1016/j.scitotenv.2022.156660

33. Lynch, K.M., R.H. Lyles, L.A. Waller, A.M. Abadi, J.E. Bell, and M.O. Gribble, 2020: Drought severity and all-cause mortality rates among adults in the United States: 1968–2014. *Environmental Health*, **19** (1), 52. https://doi.org/10.1186/s12940-020-00597-8

34. Achakulwisut, P., L.J. Mickley, and S.C. Anenberg, 2018: Drought-sensitivity of fine dust in the US Southwest: Implications for air quality and public health under future climate change. *Environmental Research Letters*, **13** (5), 054025. https://doi.org/10.1088/1748-9326/aabf20

35. Bell, J.E., C.L. Brown, K. Conlon, S. Herring, K.E. Kunkel, J. Lawrimore, G. Luber, C. Schreck, A. Smith, and C. Uejio, 2018: Changes in extreme events and the potential impacts on human health. *Journal of the Air & Waste Management Association*, **68** (4), 265–287. https://doi.org/10.1080/10962247.2017.1401017

36. Lombard, M.A., J. Daniel, Z. Jeddy, L.E. Hay, and J.D. Ayotte, 2021: Assessing the impact of drought on arsenic exposure from private domestic wells in the conterminous United States. *Environmental Science & Technology*, **55** (3), 1822–1831. https://doi.org/10.1021/acs.est.9b05835

37. New-Aaron, M., O. Abimbola, R. Mohammadi, O. Famojuro, Z. Naveed, A. Abadi, J.E. Bell, S. Bartelt-Hunt, and E.G. Rogan, 2021: Low-level groundwater atrazine in high atrazine usage Nebraska counties: Likely effects of excessive groundwater abstraction. *International Journal of Environmental Research and Public Health*, **18** (24). https://doi.org/10.3390/ijerph182413241

38. Sugg, M., J. Runkle, R. Leeper, H. Bagli, A. Golden, L.H. Handwerger, T. Magee, C. Moreno, R. Reed-Kelly, M. Taylor, and S. Woolard, 2020: A scoping review of drought impacts on health and society in North America. *Climatic Change*, **162** (3), 1177–1195. https://doi.org/10.1007/s10584-020-02848-6

39. Berman, J.D., M.R. Ramirez, J.E. Bell, R. Bilotta, F. Gerr, and N.B. Fethke, 2021: The association between drought conditions and increased occupational psychosocial stress among U.S. farmers: An occupational cohort study. *Science of The Total Environment*, **798**, 149245. https://doi.org/10.1016/j.scitotenv.2021.149245

40. Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara, 2021: The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2011048118. https://doi.org/10.1073/pnas.2011048118

41. Isaac, F., S.R. Toukhsati, M. Di Benedetto, and G.A. Kennedy, 2021: A systematic review of the impact of wildfires on sleep disturbances. *International Journal of Environmental Research and Public Health*, **18** (19), 10152. https://doi.org/10.3390/ijerph181910152

42. Silveira, S., M. Kornbluh, M.C. Withers, G. Grennan, V. Ramanathan, and J. Mishra, 2021: Chronic mental health sequelae of climate change extremes: A case study of the deadliest Californian wildfire. *International Journal of Environmental Research and Public Health*, **18** (4), 1487. https://doi.org/10.3390/ijerph18041487

43. Stokes, S.C., K.S. Romanowski, S. Sen, D.G. Greenhalgh, and T.L. Palmieri, 2021: Wildfire burn patients: A unique population. *Journal of Burn Care & Research*, **42** (5), 905–910. https://doi.org/10.1093/jbcr/irab107

44. To, P., E. Eboreime, and V.I.O. Agyapong, 2021: The impact of wildfires on mental health: A scoping review. *Behavioral Sciences*, **11** (9), 126. https://doi.org/10.3390/bs11090126

45. Gan, R.W., J. Liu, B. Ford, K. O'Dell, A. Vaidyanathan, A. Wilson, J. Volckens, G. Pfister, E.V. Fischer, J.R. Pierce, and S. Magzamen, 2020: The association between wildfire smoke exposure and asthma-specific medical care utilization in Oregon during the 2013 wildfire season. *Journal of Exposure Science & Environmental Epidemiology*, **30** (4), 618–628. https://doi.org/10.1038/s41370-020-0210-x

46. Grant, E. and J.D. Runkle, 2022: Long-term health effects of wildfire exposure: A scoping review. *The Journal of Climate Change and Health*, **6**, 100110. https://doi.org/10.1016/j.joclim.2021.100110

47. Kondo, M.C., A.J. De Roos, L.S. White, W.E. Heilman, M.H. Mockrin, C.A. Gross-Davis, and I. Burstyn, 2019: Meta-analysis of heterogeneity in the effects of wildfire smoke exposure on respiratory health in North America. *International Journal of Environmental Research and Public Health*, **16** (6), 960. https://doi.org/10.3390/ijerph16060960

48. Reid, C.E., M. Brauer, F.H. Johnston, M. Jerrett, J.R. Balmes, and C.T. Elliott, 2016: Critical review of health impacts of wildfire smoke exposure. *Environmental Health Perspectives*, **124** (9), 1334–1343. https://doi.org/10.1289/ehp.1409277

49. Wettstein, Z.S., S. Hoshiko, J. Fahimi, R.J. Harrison, W.E. Cascio, and A.G. Rappold, 2018: Cardiovascular and cerebrovascular emergency department visits associated with wildfire smoke exposure in California in 2015. *Journal of the American Heart Association*, **7** (8), e007492. https://doi.org/10.1161/jaha.117.007492

50. Anyamba, A., J.-P. Chretien, S.C. Britch, R.P. Soebiyanto, J.L. Small, R. Jepsen, B.M. Forshey, J.L. Sanchez, R.D. Smith, R. Harris, C.J. Tucker, W.B. Karesh, and K.J. Linthicum, 2019: Global disease outbreaks associated with the 2015–2016 El Niño event. *Scientific Reports*, **9** (1), 1930. https://doi.org/10.1038/s41598-018-38034-z

51. Benedict, K. and B.J. Park, 2014: Invasive fungal infections after natural disasters. *Emerging Infectious Diseases*, **20** (3), 349–355. https://doi.org/10.3201/eid2003.131230

52. Beyer, R.M., A. Manica, and C. Mora, 2021: Shifts in global bat diversity suggest a possible role of climate change in the emergence of SARS-CoV-1 and SARS-CoV-2. *Science of The Total Environment*, **767**, 145413. https://doi.org/10.1016/j.scitotenv.2021.145413

53. Carlson, C.J., G.F. Albery, C. Merow, C.H. Trisos, C.M. Zipfel, E.A. Eskew, K.J. Olival, N. Ross, and S. Bansal, 2022: Climate change increases cross-species viral transmission risk. *Nature*, **607** (7919), 555–562. https://doi.org/10.1038/s41586-022-04788-w

54. Escobar, L.E., A. Velasco-Villa, P.S. Satheshkumar, Y. Nakazawa, and P. Van de Vuurst, 2023: Revealing the complexity of vampire bat rabies "spillover transmission". *Infectious Diseases of Poverty*, **12** (1), 10. https://doi.org/10.1186/s40249-023-01062-7

55. Hayes, M.A. and A.J. Piaggio, 2018: Assessing the potential impacts of a changing climate on the distribution of a rabies virus vector. *PLoS ONE*, **13** (2), e0192887. https://doi.org/10.1371/journal.pone.0192887

56. Hueffer, K., A.J. Parkinson, R. Gerlach, and J. Berner, 2013: Zoonotic infections in Alaska: Disease prevalence, potential impact of climate change and recommended actions for earlier disease detection, research, prevention and control. *International Journal of Circumpolar Health*, **72** (1). https://doi.org/10.3402/ijch.v72i0.19562

57. Gharpure, R., M. Gleason, Z. Salah, A.J. Blackstock, D. Hess-Homeier, J.S. Yoder, I.K.M. Ali, S.A. Collier, and J.R. Cope, 2021: Geographic range of recreational water–associated primary amebic meningoencephalitis, United States, 1978–2018. *Emerging Infectious Diseases*, **27** (1), 271–274. https://doi.org/10.3201/eid2701.202119

58. Hepler, S.A., K.A. Kaufeld, K. Benedict, M. Toda, B.R. Jackson, X. Liu, and D. Kline, 2022: Integrating public health surveillance and environmental data to model presence of *Histoplasma* in the United States. *Epidemiology*, **33** (5). https://doi.org/10.1097/ede.0000000000001499

59. Jackson, M.K., C. Pelletier Keith, J. Scheftel, D. Kerkaert Joshua, L. Robinson Serina, T. McDonald, B. Bender Jeff, F. Knight Joseph, M. Ireland, and K. Nielsen, 2021: *Blastomyces dermatitidis* environmental prevalence in Minnesota: Analysis and modeling using soil collected at basal and outbreak sites. *Applied and Environmental Microbiology*, **87** (5), e01922–20. https://doi.org/10.1128/aem.01922-20

60. Uejio, C.K., S. Mak, A. Manangan, G. Luber, and K.H. Bartlett, 2015: Climatic influences on *Cryptococcus gattii* populations, Vancouver Island, Canada, 2002–2004. *Emerging Infectious Diseases*, **21** (11), 1989–96. https://doi.org/10.3201/eid2111.141161

61. Gorris, M.E., J.E. Neumann, P.L. Kinney, M. Sheahan, and M.C. Sarofim, 2021: Economic valuation of coccidioidomycosis (Valley fever) projections in the United States in response to climate change. *Weather, Climate, and Society*, **13** (1), 107–123. https://doi.org/10.1175/wcas-d-20-0036.1

62. de Perio, M.A., B.L. Materna, G.L. Sondermeyer Cooksey, D.J. Vugia, C.P. Su, S.E. Luckhaupt, J. McNary, and J.A. Wilken, 2019: Occupational coccidioidomycosis surveillance and recent outbreaks in California. *Medical Mycology*, **57** (Supplement_1), S41–S45. https://doi.org/10.1093/mmy/myy031

63. Gorris, M.E., K.K. Treseder, C.S. Zender, and J.T. Randerson, 2019: Expansion of coccidioidomycosis endemic regions in the United States in response to climate change. *GeoHealth*, **3** (10), 308–327. https://doi.org/10.1029/2019gh000209

64. McCurdy, S.A., C. Portillo-Silva, C.L. Sipan, H. Bang, and K.W. Emery, 2020: Risk for coccidioidomycosis among Hispanic farm workers, California, USA, 2018. *Emerging Infectious Diseases*, **26** (7), 1430–1437. https://doi.org/10.3201/eid2607.200024

65. Benedict, K., O.Z. McCotter, S. Brady, K. Komatsu, G.L. Sondermeyer Cooksey, A. Nguyen, S. Jain, D.J. Vugia, and B.R. Jackson, 2019: Surveillance for coccidioidomycosis—United States, 2011–2017. *MMWR Surveillance Summaries*, **68** (7), 1–15. https://doi.org/10.15585/mmwr.ss6807a1

66. California Department of Public Health, 2019: Epidemiologic Summary of Valley Fever (Coccidioidomycosis) in California, 2019. California Department of Public Health, Center for Infectious Diseases, Sacramento, CA. https://www.cdph.ca.gov/programs/cid/dcdc/cdph%20document%20library/cocciepisummary2019.pdf

67. Carey, A., M. Gorris, T. Chiller, B. Jackson, W. Beadles, and B. Webb, 2021: Epidemiology, clinical features, and outcomes of coccidioidomycosis, Utah, 2006–2015. *Emerging Infectious Disease*, **27** (9), 2269. https://doi.org/10.3201/eid2709.210751

68. Sondermeyer Cooksey, G.L., A. Nguyen, D. Vugia, and S. Jain, 2020: Regional analysis of coccidioidomycosis incidence—California, 2000–2018. *Morbidity and Mortality Weekly Report*, **69**, 1817–1821. https://doi.org/10.15585/mmwr.mm6948a4

69. NCEH, 2023: Climate Effects on Health. Centers for Disease Control and Prevention, National Center for Environmental Health. https://www.cdc.gov/climateandhealth/effects/default.htm

70. OPHDST, 2023: National Notifiable Disease Surveillance System: Notifiable Infectious Disease Tables. Centers for Disease Control and Prevention, Office of Public Health Data, Surveillance, and Technology. https://www.cdc.gov/nndss/data-statistics/infectious-tables/index.html

71. Beard, C.B., S.N. Visser, and L.R. Petersen, 2019: The need for a national strategy to address vector-borne disease threats in the United States. *Journal of Medical Entomology*, **56** (5), 1199–1203. https://doi.org/10.1093/jme/tjz074

72. Bisanzio, D., M.P. Fernández, E. Martello, R. Reithinger, and M.A. Diuk-Wasser, 2020: Current and future spatiotemporal patterns of Lyme disease reporting in the northeastern United States. *JAMA Network Open*, **3** (3), e200319. https://doi.org/10.1001/jamanetworkopen.2020.0319

73. Kugeler, K.J., A.M. Schwartz, M.J. Delorey, P.S. Mead, and A.F. Hinckley, 2021: Estimating the frequency of Lyme disease diagnoses, United States, 2010–2018. *Emerging Infectious Diseases*, **27** (2), 616–619. https://doi.org/10.3201/eid2702.202731

74. Caminade, C., K.M. McIntyre, and A.E. Jones, 2019: Impact of recent and future climate change on vector-borne diseases. *Annals of the New York Academy of Sciences*, **1436** (1), 157–173. https://doi.org/10.1111/nyas.13950

75. Gilbert, L., 2021: The impacts of climate change on ticks and tick-borne disease risk. *Annual Review of Entomology*, **66** (1), 373–388. https://doi.org/10.1146/annurev-ento-052720-094533

76. Ogden, N.H., C. Ben Beard, H.S. Ginsberg, and J.I. Tsao, 2021: Possible effects of climate change on ixodid ticks and the pathogens they transmit: Predictions and observations. *Journal of Medical Entomology*, **58** (4), 1536–1545. https://doi.org/10.1093/jme/tjaa220

77. Porter, W.T., Z.A. Barrand, J. Wachara, K. DaVall, J.R. Mihaljevic, T. Pearson, D.J. Salkeld, and N.C. Nieto, 2021: Predicting the current and future distribution of the western black-legged tick, *Ixodes pacificus*, across the western US using citizen science collections. *PLoS ONE*, **16** (1), e0244754. https://doi.org/10.1371/journal.pone.0244754

78. Sonenshine, D.E., 2018: Range expansion of tick disease vectors in North America: Implications for spread of tick-borne disease. *International Journal of Environmental Research and Public Health*, **15** (3), 478. https://doi.org/10.3390/ijerph15030478

79. Soucy, J.-P.R., A.M. Slatculescu, C. Nyiraneza, N.H. Ogden, P.A. Leighton, J.T. Kerr, and M.A. Kulkarni, 2018: High-resolution ecological niche modeling of *Ixodes scapularis* ticks based on passive surveillance data at the northern frontier of Lyme disease emergence in North America. *Vector-Borne and Zoonotic Diseases*, **18** (5), 235–242. https://doi.org/10.1089/vbz.2017.2234

80. Lippi, C.A., H.D. Gaff, A.L. White, and S.J. Ryan, 2021: Scoping review of distribution models for selected *Amblyomma* ticks and rickettsial group pathogens. *PeerJ*, **9**, e10596. https://doi.org/10.7717/peerj.10596

81. Ma, D., X. Lun, C. Li, R. Zhou, Z. Zhao, J. Wang, Q. Zhang, and Q. Liu, 2021: Predicting the potential global distribution of *Amblyomma americanum* (Acari: Ixodidae) under near current and future climatic conditions, using the maximum entropy model. *Biology*, **10** (10), 1057. https://doi.org/10.3390/biology10101057

82. Molaei, G., E.A.H. Little, S.C. Williams, and K.C. Stafford, 2019: Bracing for the worst—Range expansion of the Lone Star tick in the northeastern United States. *The New England Journal of Medicine*, **381** (23), 2189–2192. https://doi.org/10.1056/nejmp1911661

83. Raghavan, R.K., A.T. Peterson, M.E. Cobos, R. Ganta, and D. Foley, 2019: Current and future distribution of the lone star tick, *Amblyomma americanum* (L.) (Acari: Ixodidae) in North America. *PLoS ONE*, **14** (1), e0209082. https://doi.org/10.1371/journal.pone.0209082

84. Sagurova, I., A. Ludwig, N.H. Ogden, Y. Pelcat, G. Dueymes, and P. Gachon, 2019: Predicted northward expansion of the geographic range of the tick vector *Amblyomma americanum* in North America under future climate conditions. *Environmental Health Perspectives*, **127** (10), 107014. https://doi.org/10.1289/ehp5668

85. Molaei, G., E.A.H. Little, N. Khalil, B.N. Ayres, W.L. Nicholson, and C.D. Paddock, 2021: Established population of the Gulf Coast tick, *Amblyomma maculatum* (Acari: Ixodidae), infected with *Rickettsia parkeri* (Rickettsiales: Rickettsiaceae), in Connecticut. *Journal of Medical Entomology*, **58** (3), 1459–1462. https://doi.org/10.1093/jme/tjaa299

86. MacDonald, A.J., 2018: Abiotic and habitat drivers of tick vector abundance, diversity, phenology and human encounter risk in southern California. *PLoS ONE*, **13** (7), e0201665. https://doi.org/10.1371/journal.pone.0201665

87. MacDonald, A.J., S. McComb, C. O'Neill, K.A. Padgett, and A.E. Larsen, 2020: Projected climate and land use change alter western blacklegged tick phenology, seasonal host-seeking suitability and human encounter risk in California. *Global Change Biology*, **26** (10), 5459–5474. https://doi.org/10.1111/gcb.15269

88. MacDonald, A.J., C. O'Neill, M.H. Yoshimizu, K.A. Padgett, and A.E. Larsen, 2019: Tracking seasonal activity of the western blacklegged tick across California. *Journal of Applied Ecology*, **56** (11), 2562–2573. https://doi.org/10.1111/1365-2664.13490

89. McClure, M. and M.A. Diuk-Wasser, 2019: Climate impacts on blacklegged tick host-seeking behavior. *International journal for parasitology*, **49** (1), 37–47. https://doi.org/10.1016/j.ijpara.2018.08.005

90. Chowell, G., K. Mizumoto, J.M. Banda, S. Poccia, and C. Perrings, 2019: Assessing the potential impact of vector-borne disease transmission following heavy rainfall events: A mathematical framework. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **374** (1775), 20180272. https://doi.org/10.1098/rstb.2018.0272

91. Coalson, J.E., E.J. Anderson, E.M. Santos, V.M. Garcia, J.K. Romine, J.K. Luzingu, B. Dominguez, D.M. Richard, A.C. Little, M.H. Hayden, and K.C. Ernst, 2021: The complex epidemiological relationship between flooding events and human outbreaks of mosquito-borne diseases: A scoping review. *Environmental Health Perspectives*, **129** (9), 096002. https://doi.org/10.1289/ehp8887

92. Monaghan, A.J., C.A. Schmidt, M.H. Hayden, K.A. Smith, M.H. Reiskind, R. Cabell, and K.C. Ernst, 2019: A simple model to predict the potential abundance of *Aedes aegypti* mosquitoes one month in advance. *The American Journal of Tropical Medicine and Hygiene*, **100** (2), 434–437. https://doi.org/10.4269/ajtmh.17-0860

93. Blagrove, M.S.C., C. Caminade, P.J. Diggle, E.I. Patterson, K. Sherlock, G.E. Chapman, J. Hesson, S. Metelmann, P.J. McCall, G. Lycett, J. Medlock, G.L. Hughes, A. della Torre, and M. Baylis, 2020: Potential for Zika virus transmission by mosquitoes in temperate climates. *Proceedings of the Royal Society B: Biological Sciences*, **287** (1930), 20200119. https://doi.org/10.1098/rspb.2020.0119

94. Filho, W.L., S. Scheday, J. Boenecke, A. Gogoi, A. Maharaj, and S. Korovou, 2019: Climate change, health and mosquito-borne diseases: Trends and implications to the Pacific region. *International Journal of Environmental Research and Public Health*, **16** (24), 5114. https://doi.org/10.3390/ijerph16245114

95. Khan, S.U., N.H. Ogden, A.A. Fazil, P.H. Gachon, G.U. Dueymes, A.L. Greer, and V. Ng, 2020: Current and projected distributions of *Aedes aegypti* and *Ae. albopictus* in Canada and the U.S. *Environmental Health Perspectives*, **128** (5), 057007. https://doi.org/10.1289/ehp5899

96. Kraemer, M.U.G., R.C. Reiner Jr., O.J. Brady, J.P. Messina, M. Gilbert, D.M. Pigott, D. Yi, K. Johnson, L. Earl, L.B. Marczak, S. Shirude, N. Davis Weaver, D. Bisanzio, T.A. Perkins, S. Lai, X. Lu, P. Jones, G.E. Coelho, R.G. Carvalho, W. Van Bortel, C. Marsboom, G. Hendrickx, F. Schaffner, C.G. Moore, H.H. Nax, L. Bengtsson, E. Wetter, A.J. Tatem, J.S. Brownstein, D.L. Smith, L. Lambrechts, S. Cauchemez, C. Linard, N.R. Faria, O.G. Pybus, T.W. Scott, Q. Liu, H. Yu, G.R.W. Wint, S.I. Hay, and N. Golding, 2019: Past and future spread of the arbovirus vectors *Aedes aegypti* and *Aedes albopictus*. *Nature Microbiology*, **4** (5), 854–863. https://doi.org/10.1038/s41564-019-0376-y

97. Matysiak, A. and A. Roess, 2017: Interrelationship between climatic, ecologic, social, and cultural determinants affecting dengue emergence and transmission in Puerto Rico and their implications for Zika response. *Journal of Tropical Medicine*, **2017**, 1–14. https://doi.org/10.1155/2017/8947067

98. Messina, J.P., O.J. Brady, N. Golding, M.U.G. Kraemer, G.R.W. Wint, S.E. Ray, D.M. Pigott, F.M. Shearer, K. Johnson, L. Earl, L.B. Marczak, S. Shirude, N. Davis Weaver, M. Gilbert, R. Velayudhan, P. Jones, T. Jaenisch, T.W. Scott, R.C. Reiner, and S.I. Hay, 2019: The current and future global distribution and population at risk of dengue. *Nature Microbiology*, **4** (9), 1508–1515. https://doi.org/10.1038/s41564-019-0476-8

99. NCEH, 2022: Justice, Equity, Diversity, and Inclusion in Climate Adaptation Planning. Centers for Disease Control and Prevention, National Center for Environmental Health. https://www.cdc.gov/climateandhealth/jedi.htm

100. Gorris, M.E., A.W. Bartlow, S.D. Temple, D. Romero-Alvarez, D.P. Shutt, J.M. Fair, K.A. Kaufeld, S.Y. Del Valle, and C.A. Manore, 2021: Updated distribution maps of predominant *Culex* mosquitoes across the Americas. *Parasites & Vectors*, **14** (1), 547. https://doi.org/10.1186/s13071-021-05051-3

101. Keyel, A.C., A. Raghavendra, A.T. Ciota, and O. Elison Timm, 2021: West Nile virus is predicted to be more geographically widespread in New York State and Connecticut under future climate change. *Global Change Biology*, **27** (21), 5430–5445. https://doi.org/10.1111/gcb.15842

102. Shocket, M.S., A.B. Verwillow, M.G. Numazu, H. Slamani, J.M. Cohen, F. El Moustaid, J. Rohr, L.R. Johnson, and E.A. Mordecai, 2020: Transmission of West Nile and five other temperate mosquito-borne viruses peaks at temperatures between 23°C and 26°C. *eLife*, **9**, e58511. https://doi.org/10.7554/elife.58511

103. Corrin, T., R. Ackford, M. Mascarenhas, J. Greig, and L.A. Waddell, 2020: Eastern equine encephalitis virus: A scoping review of the global evidence. *Vector-Borne and Zoonotic Diseases*, **21** (5), 305–320. https://doi.org/10.1089/vbz.2020.2671

104. Diaz, A., L.L. Coffey, N. Burkett-Cadena, and J.F. Day, 2018: Reemergence of St. Louis encephalitis virus in the Americas. *Emerging Infectious Diseases*, **24** (12), 2150–2157. https://doi.org/10.3201/eid2412.180372

105. Faizah, A.N., D. Kobayashi, M. Amoa-Bosompem, Y. Higa, Y. Tsuda, K. Itokawa, K. Miura, K. Hirayama, K. Sawabe, and H. Isawa, 2021: Evaluating the competence of the primary vector, *Culex tritaeniorhynchus*, and the invasive mosquito species, *Aedes japonicus japonicus*, in transmitting three Japanese encephalitis virus genotypes. *PLoS Neglected Tropical Diseases*, **14** (12), e0008986. https://doi.org/10.1371/journal.pntd.0008986

106. Harding, S., J. Greig, M. Mascarenhas, I. Young, and L.A. Waddell, 2019: La Crosse virus: A scoping review of the global evidence. *Epidemiology & Infection*, **147**, e66. https://doi.org/10.1017/s0950268818003096

107. Little, E.A.H., M.L. Hutchinson, K.J. Price, A. Marini, J.J. Shepard, and G. Molaei, 2022: Spatiotemporal distribution, abundance, and host interactions of two invasive vectors of arboviruses, *Aedes albopictus* and *Aedes japonicus*, in Pennsylvania, USA. *Parasites & Vectors*, **15** (1), 36. https://doi.org/10.1186/s13071-022-05151-8

108. McKenzie, B.A., K. Stevens, A.E. McKenzie, J. Bozic, D. Mathias, and S. Zohdy, 2019: *Aedes* vector surveillance in the southeastern United States reveals growing threat of *Aedes japonicus japonicus* (Diptera: Culicidae) and *Aedes albopictus*. *Journal of Medical Entomology*, **56** (6), 1745–1749. https://doi.org/10.1093/jme/tjz115

109. Mogi, M., P.A. Armbruster, and N. Tuno, 2020: Differences in responses to urbanization between invasive mosquitoes, *Aedes japonicus japonicus* (Diptera: Culicidae) and *Aedes albopictus*, in their native range, Japan. *Journal of Medical Entomology*, **57** (1), 104–112. https://doi.org/10.1093/jme/tjz145

110. Reed, E.M.X., B.D. Byrd, S.L. Richards, M. Eckardt, C. Williams, and M.H. Reiskind, 2019: A statewide survey of container *Aedes* mosquitoes (Diptera: Culicidae) in North Carolina, 2016: A multiagency surveillance response to Zika using ovitraps. *Journal of Medical Entomology*, **56** (2), 483–490. https://doi.org/10.1093/jme/tjy190

111. Rowe, R.D., A. Odoi, D. Paulsen, A.C. Moncayo, and R.T. Trout Fryxell, 2020: Spatial-temporal clusters of host-seeking *Aedes albopictus*, *Aedes japonicus*, and *Aedes triseriatus* collections in a La Crosse virus endemic county (Knox County, Tennessee, USA). *PLoS ONE*, **15** (9), e0237322. https://doi.org/10.1371/journal.pone.0237322

112. Raymond, W.W., J.S. Barber, M.N. Dethier, H.A. Hayford, C.D.G. Harley, T.L. King, B. Paul, C.A. Speck, E.D. Tobin, A.E.T. Raymond, and P.S. McDonald, 2022: Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. *Ecology*, **103** (10), e3798. https://doi.org/10.1002/ecy.3798

113. Sheahan, M., C.A. Gould, J.E. Neumann, P.L. Kinney, S. Hoffmann, C. Fant, X. Wang, and M. Kolian, 2022: Examining the relationship between climate change and vibriosis in the United States: Projected health and economic impacts for the 21st century. *Environmental Health Perspectives*, **130** (8), 087007. https://doi.org/10.1289/ehp9999a

114. Baker-Austin, C., J.D. Oliver, M. Alam, A. Ali, M.K. Waldor, F. Qadri, and J. Martinez-Urtaza, 2018: *Vibrio* spp. infections. *Nature Reviews Disease Primers*, **4** (1), 1–19. https://doi.org/10.1038/s41572-018-0005-8

115. Brumfield, K.D., M. Usmani, K.M. Chen, M. Gangwar, A.S. Jutla, A. Huq, and R.R. Colwell, 2021: Environmental parameters associated with incidence and transmission of pathogenic *Vibrio* spp. *Environmental Microbiology*, **23** (12), 7314–7340. https://doi.org/10.1111/1462-2920.15716

116. Deeb, R., D. Tufford, G.I. Scott, J.G. Moore, and K. Dow, 2018: Impact of climate change on *Vibrio vulnificus* abundance and exposure risk. *Estuaries and Coasts*, **41** (8), 2289–2303. https://doi.org/10.1007/s12237-018-0424-5

117. Froelich, B.A. and D.A. Daines, 2020: In hot water: Effects of climate change on *Vibrio*–human interactions. *Environmental Microbiology*, **22** (10), 4101–4111. https://doi.org/10.1111/1462-2920.14967

118. Shultz, J.M., A. Rechkemmer, A. Rai, and K.T. McManus, 2019: Public health and mental health implications of environmentally induced forced migration. *Disaster Medicine and Public Health Preparedness*, **13** (2), 116–122. https://doi.org/10.1017/dmp.2018.27

119. Garnett, M.F., S.C. Curtin, and D.M. Stone, 2022: Suicide Mortality in the United States, 2000–2020. NCHS Data Brief No. 433. Centers for Disease Control and Prevention, National Center for Health Statistics. https://doi.org/10.15620/cdc:114217

120. SAMHSA, 2021: Key Substance Use and Mental Health Indicators in the United States: Results from the 2020 National Survey on Drug Use and Health. HHS Publication No. PEP21-07-01-003, NSDUH Series H-56. Substance Abuse and Mental Health Services Administration, Center for Behavioral Health Statistics and Quality, Rockville, MD. https://www.samhsa.gov/data/sites/default/files/reports/rpt35325/NSDUHFFRPDFWHTMLFiles2020/2020NSDUHFFR1PDFW102121.pdf

121. Bevilacqua, K., R. Rasul, S. Schneider, M. Guzman, V. Nepal, D. Banerjee, J. Schulte, and R.M. Schwartz, 2020: Understanding associations between Hurricane Harvey exposure and mental health symptoms among greater Houston-area residents. *Disaster Medicine and Public Health Preparedness*, **14** (1), 103–110. https://doi.org/10.1017/dmp.2019.141

122. Neria, Y. and J.M. Shultz, 2012: Mental health effects of Hurricane Sandy: Characteristics, potential aftermath, and response. JAMA, **308** (24), 2571–2572. https://doi.org/10.1001/jama.2012.110700

123. Raker, E.J., S.R. Lowe, M.C. Arcaya, S.T. Johnson, J. Rhodes, and M.C. Waters, 2019: Twelve years later: The long-term mental health consequences of Hurricane Katrina. *Social Science & Medicine*, **242**, 112610. https://doi.org/10.1016/j.socscimed.2019.112610

124. Torres-Mendoza, Y., A. Kerr, A.H. Schnall, C. Blackmore, and S.D. Hartley, 2021: Community assessment for mental and physical health effects after Hurricane Irma—Florida Keys, May 2019. *Morbidity and Mortality Weekly Report*, **70** (26), 937–941. https://doi.org/10.15585/mmwr.mm7026a1

125. Burke, M., F. González, P. Baylis, S. Heft-Neal, C. Baysan, S. Basu, and S. Hsiang, 2018: Higher temperatures increase suicide rates in the United States and Mexico. *Nature Climate Change*, **8** (8), 723–729. https://doi.org/10.1038/s41558-018-0222-x

126. Reo, N.J. and L.A. Ogden, 2018: Anishnaabe Aki: An indigenous perspective on the global threat of invasive species. *Sustainability Science*, **13**, 1443–1452. https://doi.org/10.1007/s11625-018-0571-4

127. Tribal Adaptation Menu Team, 2019: Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu. Great Lakes Indian Fish and Wildlife Commission, Odanah, WI, 54 pp. https://forestadaptation.org/tribal-climate-adaptation-menu

128. Middleton, J., A. Cunsolo, A. Jones-Bitton, C.J. Wright, and S.L. Harper, 2020: Indigenous mental health in a changing climate: A systematic scoping review of the global literature. *Environmental Research Letters*, **15** (5), 053001. https://doi.org/10.1088/1748-9326/ab68a9

129. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

130. Thiery, W., S. Lange, J. Rogelj, C.-F. Schleussner, L. Gudmundsson, S.I. Seneviratne, M. Andrijevic, K. Frieler, K. Emanuel, T. Geiger, D.N. Bresch, F. Zhao, S.N. Willner, M. Büchner, J. Volkholz, N. Bauer, J. Chang, P. Ciais, M. Dury, L. François, M. Grillakis, S.N. Gosling, N. Hanasaki, T. Hickler, V. Huber, A. Ito, J. Jägermeyr, N. Khabarov, A. Koutroulis, W. Liu, W. Lutz, M. Mengel, C. Müller, S. Ostberg, C.P.O. Reyer, T. Stacke, and Y. Wada, 2021: Intergenerational inequities in exposure to climate extremes. *Science*, **374** (6564), 158–160. https://doi.org/10.1126/science.abi7339

131. Hughes, K., M.A. Bellis, K.A. Hardcastle, D. Sethi, A. Butchart, C. Mikton, L. Jones, and M.P. Dunne, 2017: The effect of multiple adverse childhood experiences on health: A systematic review and meta-analysis. *The Lancet Public Health*, **2** (8), e356–e366. https://doi.org/10.1016/s2468-2667(17)30118-4

132. Hickman, C., E. Marks, P. Pihkala, S. Clayton, R.E. Lewandowski, E.E. Mayall, B. Wray, C. Mellor, and L. van Susteren, 2021: Climate anxiety in children and young people and their beliefs about government responses to climate change: A global survey. *The Lancet Planetary Health*, **5** (12), e863–e873. https://doi.org/10.1016/s2542-5196(21)00278-3

133. Coffey, Y., N. Bhullar, J. Durkin, M.S. Islam, and K. Usher, 2021: Understanding eco-anxiety: A systematic scoping review of current literature and identified knowledge gaps. *The Journal of Climate Change and Health*, **3**, 100047. https://doi.org/10.1016/j.joclim.2021.100047

134. Joyce, S., F. Shand, J. Tighe, S.J. Laurent, R.A. Bryant, and S.B. Harvey, 2018: Road to resilience: A systematic review and meta-analysis of resilience training programmes and interventions. *BMJ Open*, **8** (6), e017858. https://doi.org/10.1136/bmjopen-2017-017858

135. Rousell, D. and A. Cutter-Mackenzie-Knowles, 2020: A systematic review of climate change education: Giving children and young people a 'voice' and a 'hand' in redressing climate change. *Children's Geographies*, **18** (2), 191–208. https://doi.org/10.1080/14733285.2019.1614532

136. Sanson, A. and M. Bellemo, 2021: Children and youth in the climate crisis. *BJPsych Bulletin*, **45** (4), 205–209. https://doi.org/10.1192/bjb.2021.16

137. Semenza, J.C., J. Rocklöv, and K.L. Ebi, 2022: Climate change and cascading risks from infectious disease. *Infectious Diseases and Therapy*, **11** (4), 1371–1390. https://doi.org/10.1007/s40121-022-00647-3

138. Sheridan, S.C., W. Zhang, X. Deng, and S. Lin, 2021: The individual and synergistic impacts of windstorms and power outages on injury ED visits in New York State. *Science of The Total Environment*, **797**, 149199. https://doi.org/10.1016/j.scitotenv.2021.149199

139. Occupational Safety and Health Administration, 2021: Heat injury and illness prevention in outdoor and indoor work settings. *Federal Register*, **86** (205), 59309–59326. https://www.govinfo.gov/content/pkg/FR-2021-10-27/pdf/2021-23250.pdf

140. Park, R.J., N. Pankratz, and A.P. Behrer, 2021: Temperature, Workplace Safety, and Labor Market Inequality. IZA DP No. 14560. IZA Institute of Labor Economics. https://docs.iza.org/dp14560.pdf

141. Spector, J.T., Y.J. Masuda, N.H. Wolff, M. Calkins, and N. Seixas, 2019: Heat exposure and occupational injuries: Review of the literature and implications. *Current Environmental Health Reports*, **6** (4), 286–296. https://doi.org/10.1007/s40572-019-00250-8

142. Nerbass, F.B., R. Pecoits-Filho, W.F. Clark, J.M. Sontrop, C.W. McIntyre, and L. Moist, 2017: Occupational heat stress and kidney health: From farms to factories. *Kidney International Reports*, **2** (6), 998–1008. https://doi.org/10.1016/j.ekir.2017.08.012

143. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

144. Licker, R., K. Dahl, and J.T. Abatzoglou, 2022: Quantifying the impact of future extreme heat on the outdoor work sector in the United States. *Elementa: Science of the Anthropocene*, **10** (1), 00048. https://doi.org/10.1525/elementa.2021.00048

145. Neidell, M., J.G. Zivin, M. Sheahan, J. Willwerth, C. Fant, M. Sarofim, and J. Martinich, 2021: Temperature and work: Time allocated to work under varying climate and labor market conditions. *PLoS ONE*, **16** (8), 0254224. https://doi.org/10.1371/journal.pone.0254224

146. Schulte, P.A., A. Bhattacharya, C.R. Butler, H.K. Chun, B. Jacklitsch, T. Jacobs, M. Kiefer, J. Lincoln, S. Pendergrass, J. Shire, J. Watson, and G.R. Wagner, 2016: Advancing the framework for considering the effects of climate change on worker safety and health. *Journal of Occupational and Environmental Hygiene*, **13** (11), 847–865. https://doi.org/10.1080/15459624.2016.1179388

147. Clayton, S., C. Manning, M. Speiser, and A.N. Hill, 2021: Mental Health and Our Changing Climate: Impacts, Inequities, Responses. American Psychological Association and ecoAmerica, Washington, DC. https://ecoamerica.org/wp-content/uploads/2021/11/mental-health-climate-change-2021-ea-apa.pdf

148. Lancet Countdown, 2020: Compounding Crises of Our Time During Hurricane Laura. 2020 Case Study 1. Lancet Countdown. https://www.lancetcountdownus.org/2020-case-study-1/

149. WHO, 2021: WHO's 10 Calls for Climate Action to Assure Sustained Recovery From COVID-19: Global Health Workforce Urges Action to Avert Health Catastrophe. World Health Organization. https://www.who.int/news/item/11-10-2021-who-s-10-calls-for-climate-action-to-assure-sustained-recovery-from-covid-19

150. Lancet Countdown, 2021: 2021 Lancet Countdown on Health and Climate Change: Policy Brief for the United States of America. Salas, R.N., P.K. Lester, and J.J. Hess, Eds. Lancet Countdown, London, UK. https://www.lancetcountdownus.org/2021-lancet-countdown-us-brief/

151. CSB, 2018: Organic Peroxide Decomposition, Release, and Fire at Arkema Crosby Following Hurricane Harvey Flooding. Report No. 2017-08-I-TX. U.S. Chemical Safety and Hazard Investigation Board, Crosby, TX. https://www.csb.gov/file.aspx?documentid=6068

152. CSD and TEJAS, 2016: Double Jeopardy in Houston: Acute and Chronic Chemical Exposures Pose Disproportionate Risks for Marginalized Communities. Center for Science and Democracy at the Union of Concerned Scientists and Texas Environmental Justice Advocacy Services, 26 pp. https://www.ucsusa.org/sites/default/files/attach/2016/10/ucs-double-jeopardy-in-houston-full-report-2016.pdf

153. Elliott, M.R., Y. Wang, R.A. Lowe, and P.R. Kleindorfer, 2004: Environmental justice: Frequency and severity of US chemical industry accidents and the socioeconomic status of surrounding communities. *Journal of Epidemiology and Community Health*, **58** (1), 24–30. https://doi.org/10.1136/jech.58.1.24

154. EPA, 2016: Regulatory Impact Analysis: Accidental Release Prevention Requirements: Risk Management Programs Under the Clean Air Act, Section 112(r)(7). U.S. Environmental Protection Agency, Office of Emergency Management, Washington, DC. https://www.regulations.gov/document/EPA-HQ-OEM-2015-0725-0734

155. Fleischman, L. and M. Franklin, 2017: Fumes Across the Fence-Line: The Health Impacts of Air Pollution from Oil & Gas Facilities on African American Communities. National Association for the Advancement of Colored People and Clean Air Task Force. https://naacp.org/resources/fumes-across-fence-line-health-impacts-air-pollution-oil-gas-facilities-african-american

156. Flores, D., C. Kalman, M. Mabson, and D. Minovi, 2021: Preventing "Double Disasters". Center for Progressive Reform, Earthjustice, and Union of Concerned Scientists. https://cpr-assets.s3.amazonaws.com/documents/preventing-double-disasters-final.pdf

157. Flores, D., D. Minovi, and J. Clark, 2021: Tanks for Nothing: The Decades-Long Failure to Protect the Public from Hazardous Chemical Spills. Center for Progressive Reform. http://progressivereform.org/our-work/energy-environment/tanks-for-nothing-ast-rpt/

158. Frank, A. and S. Moulton, 2014: Kids in Danger Zones: One in Three U.S. Schoolchildren at Risk from Chemical Catastrophes. Center for Effective Government. https://search.issuelab.org/resource/kids-in-danger-zones-one-in-three-u-s-schoolchildren-at-risk-from-chemical-catastrophes.html

159. Orum, P., R. Moore, M. Roberts, and J. Sanchez, 2014: Who's in Danger? Race, Poverty, and Chemical Disasters: A Demographic Analysis of Chemical Disasters Vulnerability Zones. Environmental Justice and Health Alliance for Chemical Policy Reform. https://comingcleaninc.org/assets/media/images/Reports/Who's%20in%20Danger%20Report%20FINAL.pdf

160. Starbuck, A. and R. White, 2016: Living in the Shadow of Danger: Poverty, Race, and Unequal Chemicals Facility Hazards. Center for Effective Government. https://www.foreffectivegov.org/shadow-of-danger

161. White, R., 2018: Life at the Fenceline: Understanding Cumulative Health Hazards in Environmental Justice Communities. Coming Clean, The Environmental Justice Health Alliance for Chemical Policy Reform, and the Campaign for Healthier Solutions. https://ej4all.org/life-at-the-fenceline

162. Wilson, A., J. Patterson, K. Wasserman, A. Starbuck, A. Sartor, J. Hatcher, J. Fleming, and K. Fink, 2012: Coal Blooded: Putting Profits Before People. Morris, M.W., Ed. National Association for the Advancement of Colored People, Indigenous Environmental Network, and Little Village Environmental Justice Organization, 128 pp. https://naacp.org/resources/coal-blooded-putting-profits-people

163. Asian Pacific Environmental Network, Central Coast Alliance for a Sustainable Economy, Physicians for Social Responsibility - Los Angeles, Public Health Institute, WE ACT for Environmental Justice, UC Berkeley Sustainability and Health Equity Lab, UC Los Angeles, Fielding School of Public Health, and Climate Central, 2020: Toxic Tides Project. University of California, Berkeley. https://sites.google.com/berkeley.edu/toxictides/home

164. Coffey, E., K. Waltz, D. Chizewer, E.A. Benfer, M.N. Templeton, and R. Weinstock, 2020: Poisonous Homes: The Fight for Environmental Justice in Federally Assisted Housing. Shriver Center on Poverty Law. https://www.povertylaw.org/wp-content/uploads/2020/06/environmental_justice_report_final-rev2.pdf

165. Doeffinger, T. and J.W. Hall, 2021: Assessing water security across scales: A case study of the United States. *Applied Geography*, **134**, 102500. https://doi.org/10.1016/j.apgeog.2021.102500

166. Seligman, H.K. and S.A. Berkowitz, 2019: Aligning programs and policies to support food security and public health goals in the United States. *Annual Review of Public Health*, **40** (1), 319–337. https://doi.org/10.1146/annurev-publhealth-040218-044132

167. Greer, R.A., 2020: A review of public water infrastructure financing in the United States. *Wiley Interdisciplinary Reviews: Water*, **7** (5), e1472. https://doi.org/10.1002/wat2.1472

168. Jones, L. and C. Ingram Jani, 2022: Invited perspective: Tribal water issues exemplified by the Navajo Nation. *Environmental Health Perspectives*, **130** (12), 121301. https://doi.org/10.1289/EHP12187

169. Baum, A., M.L. Barnett, J. Wisnivesky, and M.D. Schwartz, 2019: Association between a temporary reduction in access to health care and long-term changes in hypertension control among veterans after a natural disaster. *JAMA Network Open*, **2** (11), e1915111. https://doi.org/10.1001/jamanetworkopen.2019.15111

170. Rudowitz, R., D. Rowland, and A. Shartzer, 2006: Health care in New Orleans before and after Hurricane Katrina. *Health Affairs*, **25** (Supplement 1), W393–W406. https://doi.org/10.1377/hlthaff.25.w393

171. Nogueira, L.M., L. Sahar, J.A. Efstathiou, A. Jemal, and K.R. Yabroff, 2019: Association between declared hurricane disasters and survival of patients with lung cancer undergoing radiation treatment. *Journal of the American Medical Association*, **322** (3), 269. https://doi.org/10.1001/jama.2019.7657

172. Lurie, N., K. Finne, C. Worrall, M. Jauregui, T. Thaweethai, G. Margolis, and J. Kelman, 2015: Early dialysis and adverse outcomes after Hurricane Sandy. *American Journal of Kidney Diseases*, **66** (3), 507–512. https://doi.org/10.1053/j.ajkd.2015.04.050

173. Fant, C., J.M. Jacobs, P. Chinowsky, W. Sweet, N. Weiss, J.E. Sias, J. Martinich, and J.E. Neumann, 2021: Mere nuisance or growing threat? The physical and economic impact of high tide flooding on US road networks. *Journal of Infrastructure Systems*, **27** (4), 04021044. https://doi.org/10.1061/(asce)is.1943-555x.0000652

174. Donatuto, J., L. Campbell, C. Cooley, M. Cruz, J. Doyle, M. Eggers, T. Farrow Ferman, S. Gaughen, P. Hardison, C. Jones, D. Marks-Marino, A. Pairis, W. Red Elk, D. Sambo Dorough, and C. Sanders, 2021: Ch. 5. Health & wellbeing. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 159–173. http://nau.edu/stacc2021

175. Schramm, P.J., A.L.A. Janabi, L.W. Campbell, J.L. Donatuto, and S.C. Gaughen, 2020: How Indigenous communities are adapting to climate change: Insights from the Climate-Ready Tribes Initiative. *Health Affairs*, **39** (12), 2153–2159. https://doi.org/10.1377/hlthaff.2020.00997

176. Ford, J.D., N. King, E.K. Galappaththi, T. Pearce, G. McDowell, and S.L. Harper, 2020: The resilience of Indigenous peoples to environmental change. *One Earth*, **2** (6), 532–543. https://doi.org/10.1016/j.oneear.2020.05.014

177. Tiatia-Seath, J., T. Tupou, and I. Fookes, 2020: Climate change, mental health, and well-being for Pacific peoples: A literature review. *The Contemporary Pacific*, **32** (2), 399–430. https://doi.org/10.1353/cp.2020.0035

178. Stein, P.J.S. and M.A. Stein, 2022: Climate change and the right to health of people with disabilities. *The Lancet Global Health*, **10** (1), e24–e25. https://doi.org/10.1016/s2214-109x(21)00542-8

179. Engelman, A., L. Craig, and A. Iles, 2022: Global disability justice in climate disasters: Mobilizing people with disabilities as change agents. *Health Affairs*, **41** (10), 1496–1504. https://doi.org/10.1377/hlthaff.2022.00474

180. Elser, H., R.M. Parks, N. Moghavem, M.V. Kiang, N. Bozinov, V.W. Henderson, D.H. Rehkopf, and J.A. Casey, 2021: Anomalously warm weather and acute care visits in patients with multiple sclerosis: A retrospective study of privately insured individuals in the US. *PLoS Medicine*, **18** (4), e1003580. https://doi.org/10.1371/journal.pmed.1003580

181. Chakraborty, J., 2022: Disparities in exposure to fine particulate air pollution for people with disabilities in the US. *Science of The Total Environment*, **842**, 156791. https://doi.org/10.1016/j.scitotenv.2022.156791

182. Tessum, C.W., D.A. Paolella, S.E. Chambliss, J.S. Apte, J.D. Hill, and J.D. Marshall, 2021: $PM_{2.5}$ polluters disproportionately and systemically affect people of color in the United States. *Science Advances*, **7** (18), 4491. https://doi.org/10.1126/sciadv.abf4491

183. Wu, X., R.C. Nethery, M.B. Sabath, D. Braun, and F. Dominici, 2020: Air pollution and COVID-19 mortality in the United States: Strengths and limitations of an ecological regression analysis. *Science Advances*, **6** (45), 4049. https://doi.org/10.1126/sciadv.abd4049

184. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. https://doi.org/10.3390/cli8010012

185. Lane, H.M., R. Morello-Frosch, J.D. Marshall, and J.S. Apte, 2022: Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environmental Science & Technology Letters*, **9** (4), 345–350. https://doi.org/10.1021/acs.estlett.1c01012

186. Morello-Frosch, R., M. Pastor, J. Sadd, and S.B. Shonkoff, 2009: The Climate Gap: Inequalities in How Climate Change Hurts Americans & How to Close the Gap. University of California, Berkeley, Program for Environmnetal and Regional Equity, 31 pp. https://dornsife.usc.edu/eri/publications/the-climate-gap-inequalities-in-how-climate-change-hurts-americans-how-to-close-the-gap/

187. Nardone, A., J.A. Casey, R. Morello-Frosch, M. Mujahid, J.R. Balmes, and N. Thakur, 2020: Associations between historical residential redlining and current age-adjusted rates of emergency department visits due to asthma across eight cities in California: An ecological study. *The Lancet Planetary Health*, **4** (1), e24–e31. https://doi.org/10.1016/s2542-5196(19)30241-4

188. Berberian, A.G., D.J.X. Gonzalez, and L.J. Cushing, 2022: Racial disparities in climate change-related health effects in the United States. *Current Environmental Health Reports*, **9** (3), 451–464. https://doi.org/10.1007/s40572-022-00360-w

189. Thind, M.P.S., C.W. Tessum, I.L. Azevedo, and J.D. Marshall, 2019: Fine particulate air pollution from electricity generation in the US: Health impacts by race, income, and geography. *Environmental Science & Technology*, **53** (23), 14010–14019. https://doi.org/10.1021/acs.est.9b02527

190. James, S.E., J.L. Herman, S. Rankin, M. Keisling, L. Mottet, and M. Anafi, 2016: The Report of the 2015 US Transgender Survey. National Center for Transgender Equality, Washington, DC. https://transequality.org/sites/default/files/docs/usts/USTS-Full-Report-Dec17.pdf

191. Semega, J., M. Kollar, J. Creamer, and A. Mohanty, 2020: Income and Poverty in the United States: 2018. U.S. Census Bureau, Current Population Reports, P60-266(RV). U.S. Government Printing Office, Washington, DC. https://www.census.gov/library/publications/2019/demo/p60-266.html

192. Belsey-Priebe, M., D. Lyons, and J.J. Buonocore, 2021: COVID-19's impact on American women's food insecurity foreshadows vulnerabilities to climate change. *International Journal of Environmental Research and Public Health*, **18** (13). https://doi.org/10.3390/ijerph18136867

193. Goldsmith, L., V. Raditz, and M. Méndez, 2022: Queer and present danger: Understanding the disparate impacts of disasters on LGBTQ+ communities. *Disasters*, **46** (4), 946–973. https://doi.org/10.1111/disa.12509

194. Jeffers, N.K. and N. Glass, 2020: Integrative review of pregnancy and birth outcomes after exposure to a hurricane. *Journal of Obstetric, Gynecologic & Neonatal Nursing*, **49** (4), 348–360. https://doi.org/10.1016/j.jogn.2020.04.006

195. He, S., T. Kosatsky, A. Smargiassi, M. Bilodeau-Bertrand, and N. Auger, 2018: Heat and pregnancy-related emergencies: Risk of placental abruption during hot weather. *Environment International*, **111**, 295–300. https://doi.org/10.1016/j.envint.2017.11.004

196. Hoyert, D.L., 2023: Maternal Mortality Rates in the United States, 2021. Centers for Disease Control and Prevention, National Center for Health Statistics. https://doi.org/10.15620/cdc:124678

197. Cushing, L., R. Morello-Frosch, and A. Hubbard, 2022: Extreme heat and its association with social disparities in the risk of spontaneous preterm birth. *Paediatric and Perinatal Epidemiology*, **36** (1), 13–22. https://doi.org/10.1111/ppe.12834

198. Smith, G.S., E. Anjum, C. Francis, L. Deanes, and C. Acey, 2022: Climate change, environmental disasters, and health inequities: The underlying role of structural inequalities. *Current Environmental Health Reports*, **9** (1), 80–89. https://doi.org/10.1007/s40572-022-00336-w

199. Nomura, Y., J.H. Newcorn, C. Ginalis, C. Heitz, J. Zaki, F. Khan, M. Nasrin, K. Sie, D. DeIngeniis, and Y.L. Hurd, 2023: Prenatal exposure to a natural disaster and early development of psychiatric disorders during the preschool years: Stress in pregnancy study. *Journal of Child Psychology and Psychiatry*. https://doi.org/10.1111/jcpp.13698

200. Dominey-Howes, D., A. Gorman-Murray, and S. McKinnon, 2014: Queering disasters: On the need to account for LGBTI experiences in natural disaster contexts. *Gender, Place & Culture*, **21** (7), 905–918. https://doi.org/10.1080/0966369x.2013.802673

201. Haskell, B., 2014: Sexuality and Natural Disaster: Challenges of LGBT Communities Facing Hurricane Katrina. Social Science Research Network. https://doi.org/10.2139/ssrn.2513650

202. Vinyeta, K., K. Powys Whyte, and K. Lynn, 2015: Climate Change Through an Intersectional Lens: Gendered Vulnerability and Resilience in Indigenous Communities in the United States. Gen. Tech. Rep. PNW-GTR-923. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 72 pp. https://doi.org/10.2737/pnw-gtr-923

203. Stukes, P.A. 2014: A Caravan of Hope-Gay Christian Service: Exploring Social Vulnerability and Capacity-Building of Lesbian, Gay, Bisexual, Transgender and Intersex Identified Individuals and Organizational Advocacy in Two Post Katrina Disaster Environments. Doctor of Philosophy, Texas Woman's University. https://hdl.handle.net/11274/11265

204. Simmonds, K.E., J. Jenkins, B. White, P.K. Nicholas, and J. Bell, 2022: Health impacts of climate change on gender diverse populations: A scoping review. *Journal of Nursing Scholarship*, **54** (1), 81–91. https://doi.org/10.1111/jnu.12701

205. Hess, J.J., N. Ranadive, C. Boyer, L. Aleksandrowicz, S.C. Anenberg, K. Aunan, K. Belesova, M.L. Bell, S. Bickersteth, K. Bowen, M. Burden, D. Campbell-Lendrum, E. Carlton, G. Cissé, F. Cohen, H. Dai, A.D. Dangour, P. Dasgupta, H. Frumkin, P. Gong, R.J. Gould, A. Haines, S. Hales, I. Hamilton, T. Hasegawa, M. Hashizume, Y. Honda, D.E. Horton, A. Karambelas, H. Kim, S.E. Kim, P.L. Kinney, I. Kone, K. Knowlton, J. Lelieveld, V.S. Limaye, Q. Liu, L. Madaniyazi, M.E. Martinez, D.L. Mauzerall, J. Milner, T. Neville, M. Nieuwenhuijsen, S. Pachauri, F. Perera, H. Pineo, J.V. Remais, R.K. Saari, J. Sampedro, P. Scheelbeek, J. Schwartz, D. Shindell, P. Shyamsundar, T.J. Taylor, C. Tonne, D.V. Vuuren, C. Wang, N. Watts, J.J. West, P. Wilkinson, S.A. Wood, J. Woodcock, A. Woodward, Y. Xie, Y. Zhang, and K.L. Ebi, 2020: Guidelines for modeling and reporting health effects of climate change mitigation actions. *Environmental Health Perspectives*, **128** (11), 115001. https://doi.org/10.1289/ehp6745

206. Quintana, A.V., R. Venkatraman, S.B. Coleman, D. Martins, and S.H. Mayhew, 2021: COP26: An opportunity to shape climate-resilient health systems and research. *The Lancet Planetary Health*, **5** (12), e852–e853. https://doi.org/10.1016/s2542-5196(21)00289-8

207. WHO, 2015: Operational Framework for Building Climate Resilient Health Systems. World Health Organization, Geneva, Switzerland, 47 pp. https://apps.who.int/iris/handle/10665/189951

208. Zhang, W. and G. Villarini, 2020: Deadly compound heat stress-flooding hazard across the central United States. *Geophysical Research Letters*, **47** (15), e2020GL089185. https://doi.org/10.1029/2020gl089185

209. Manangan, A.P. and B. Gillespie, 2022: Environmental Health Nexus Webinar—Climate Change and Health: The Risks to Community Health and Healthcare Utilization. Centers for Disease Control and Prevention, National Center for Environmental Health, Division of Environmental Health Science and Practice. https://www.cdc.gov/nceh/ehsp/ehnexus/learn/documents/hrsa-webinar_march-17-2022-508.pdf

210. Rublee, C., 2020: Living in a thin dark line: How can we make healthcare systems climate resilient? *BMJ Opinion*. https://blogs.bmj.com/bmj/2020/09/15/living-in-a-thin-dark-line-how-can-we-make-healthcare-systems-climate-resilient/

211. Eckelman, M.J., K. Huang, R. Lagasse, E. Senay, R. Dubrow, and J.D. Sherman, 2020: Health care pollution and public health damage in the United States: An update. *Health Affairs*, **39** (12), 2071–2079. https://doi.org/10.1377/hlthaff.2020.01247

212. Lenzen, M., A. Malik, M. Li, J. Fry, H. Weisz, P.-P. Pichler, L.S.M. Chaves, A. Capon, and D. Pencheon, 2020: The environmental footprint of health care: A global assessment. *The Lancet Planetary Health*, **4** (7), 271–279. https://doi.org/10.1016/s2542-5196(20)30121-2

213. Lelieveld, J., K. Klingmüller, A. Pozzer, R.T. Burnett, A. Haines, and V. Ramanathan, 2019: Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (15), 7192–7197. https://doi.org/10.1073/pnas.1819989116

214. Fu, P., X. Guo, F.M.H. Cheung, and K.K.L. Yung, 2019: The association between $PM_{2.5}$ exposure and neurological disorders: A systematic review and meta-analysis. *Science of The Total Environment*, **655**, 1240–1248. https://doi.org/10.1016/j.scitotenv.2018.11.218

215. Armstrong, P., B. Jackson, D. Haselow, V. Fields, M. Ireland, C. Austin, K. Signs, V. Fialkowski, R. Patel, P. Ellis, P. Iwen, C. Pedati, S. Gibbons-Burgener, J. Anderson, T. Dobbs, S. Davidson, M. McIntyre, K. Warren, J. Midla, N. Luong, and K. Benedict, 2018: Multistate epidemiology of histoplasmosis, United States, 2011–2014. *Emerging Infectious Disease Journal*, **24** (3), 425. https://doi.org/10.3201/eid2403.171258

216. Gray, E.B. and B.L. Herwaldt, 2019: Babesiosis surveillance—United States, 2011–2015. *Morbidity and Mortality Weekly Report Surveillance Summaries*, **68** (6), 1–11. https://doi.org/10.15585/mmwr.ss6806a1

217. Groseclose, S.L. and D.L. Buckeridge, 2017: Public health surveillance systems: Recent advances in their use and evaluation. *Annual Review of Public Health*, **38** (1), 57–79. https://doi.org/10.1146/annurev-publhealth-031816-044348

218. Bartlow, A.W., C. Manore, C. Xu, K.A. Kaufeld, S. Del Valle, A. Ziemann, G. Fairchild, and J.M. Fair, 2019: Forecasting zoonotic infectious disease response to climate change: Mosquito vectors and a changing environment. *Veterinary Sciences*, **6** (2), 40. https://doi.org/10.3390/vetsci6020040

219. Morin, C.W., J.C. Semenza, J.M. Trtanj, G.E. Glass, C. Boyer, and K.L. Ebi, 2018: Unexplored opportunities: Use of climate- and weather-driven early warning systems to reduce the burden of infectious diseases. *Current Environmental Health Reports*, **5** (4), 430–438. https://doi.org/10.1007/s40572-018-0221-0

220. Wimberly, M.C., J.K. Davis, M.B. Hildreth, and J.L. Clayton, 2022: Integrated forecasts based on public health surveillance and meteorological data predict West Nile virus in a high-risk region of North America. *Environmental Health Perspectives*, **130** (8), 087006. https://doi.org/10.1289/ehp10287

221. Khan, I., F. Hou, and H.P. Le, 2021: The impact of natural resources, energy consumption, and population growth on environmental quality: Fresh evidence from the United States of America. *Science of The Total Environment*, **754**, 142222. https://doi.org/10.1016/j.scitotenv.2020.142222

222. Vespa, J., D.M. Armstrong, and L. Medina, 2018: Demographic Turning Points for the United States: Population Projections for 2020 to 2060. P25-1144. U.S. Census Bureau. https://www.census.gov/library/publications/2020/demo/p25-1144.html

223. Lo, Y.T.E., D.M. Mitchell, A. Gasparrini, A.M. Vicedo-Cabrera, K.L. Ebi, P.C. Frumhoff, R.J. Millar, W. Roberts, F. Sera, S. Sparrow, P. Uhe, and G. Williams, 2019: Increasing mitigation ambition to meet the Paris Agreement's temperature goal avoids substantial heat-related mortality in U.S. cities. *Science Advances*, **5** (6), 4373. https://doi.org/10.1126/sciadv.aau4373

224. Rohat, G., O. Wilhelmi, J. Flacke, A. Monaghan, J. Gao, M. van Maarseveen, and H. Dao, 2021: Assessing urban heat-related adaptation strategies under multiple futures for a major U.S. city. *Climatic Change*, **164** (3), 61. https://doi.org/10.1007/s10584-021-02990-9

225. Vanos, J.K., J.W. Baldwin, O. Jay, and K.L. Ebi, 2020: Simplicity lacks robustness when projecting heat-health outcomes in a changing climate. *Nature Communications*, **11** (1), 6079. https://doi.org/10.1038/s41467-020-19994-1

226. Wang, Y., F. Nordio, J. Nairn, A. Zanobetti, and J.D. Schwartz, 2018: Accounting for adaptation and intensity in projecting heat wave-related mortality. *Environmental Research*, **161**, 464–471. https://doi.org/10.1016/j.envres.2017.11.049

227. Wilhelmi, O.V., P.D. Howe, M.H. Hayden, and C.R. O'Lenick, 2021: Compounding hazards and intersecting vulnerabilities: Experiences and responses to extreme heat during COVID-19. *Environmental Research Letters*, **16** (8), 084060. https://doi.org/10.1088/1748-9326/ac1760

228. Reames, T.G., D.M. Daley, and J.C. Pierce, 2021: Exploring the nexus of energy burden, social capital, and environmental quality in shaping health in US counties. *International Journal of Environmental Research and Public Health*, **18** (2), 620. https://doi.org/10.3390/ijerph18020620

229. Shields, L., 2020: Bolstering Federal Energy Assistance and Weatherization With State Clean Energy Programs. National Conference of State Legislators. https://www.ncsl.org/energy/bolstering-federal-energy-assistance-and-weatherization-with-state-clean-energy-programs

230. Tonn, B., E. Rose, and B. Hawkins, 2018: Evaluation of the U.S. Department of Energy's Weatherization Assistance Program: Impact results. *Energy Policy*, **118**, 279–290. https://doi.org/10.1016/j.enpol.2018.03.051

231. Tonn, B., E. Rose, B. Hawkins, and M. Marincic, 2021: Health and financial benefits of weatherizing low-income homes in the southeastern United States. *Building and Environment*, **197**, 107847. https://doi.org/10.1016/j.buildenv.2021.107847

232. Fisk, W.J., B.C. Singer, and W.R. Chan, 2020: Association of residential energy efficiency retrofits with indoor environmental quality, comfort, and health: A review of empirical data. *Building and Environment*, **180**, 107067. https://doi.org/10.1016/j.buildenv.2020.107067

233. Abel, D.W., T. Holloway, M. Harkey, P. Meier, D. Ahl, V.S. Limaye, and J.A. Patz, 2018: Air-quality-related health impacts from climate change and from adaptation of cooling demand for buildings in the eastern United States: An interdisciplinary modeling study. *PLoS Medicine*, **15** (7), e1002599. https://doi.org/10.1371/journal.pmed.1002599

234. Jay, O., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, and K.L. Ebi, 2021: Reducing the health effects of hot weather and heat extremes: From personal cooling strategies to green cities. *The Lancet*, **398** (10301), 709–724. https://doi.org/10.1016/s0140-6736(21)01209-5

235. Sailor, D.J., A. Baniassadi, C.R. O'Lenick, and O.V. Wilhelmi, 2019: The growing threat of heat disasters. *Environmental Research Letters*, **14** (5), 054006. https://doi.org/10.1088/1748-9326/ab0bb9

236. Stone Jr., B., E. Mallen, M. Rajput, C.J. Gronlund, A.M. Broadbent, E.S. Krayenhoff, G. Augenbroe, M.S. O'Neill, and M. Georgescu, 2021: Compound climate and infrastructure events: How electrical grid failure alters heat wave risk. *Environmental Science & Technology*, **55** (10), 6957–6964. https://doi.org/10.1021/acs.est.1c00024

237. USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/nca4.2018

238. Williams, A.A., A. Baniassadi, P. Izaga Gonzalez, J.J. Buonocore, J.G. Cedeno-Laurent, and H.W. Samuelson, 2020: Health and climate benefits of heat adaptation strategies in single-family residential buildings. *Frontiers in Sustainable Cities*, **2**, 561828. https://doi.org/10.3389/frsc.2020.561828

239. Grocholski, B., 2020: Cooling in a warming world. *Science*, **370** (6518), 776–777. https://doi.org/10.1126/science.abf1931

240. Khosla, R., N.D. Miranda, P.A. Trotter, A. Mazzone, R. Renaldi, C. McElroy, F. Cohen, A. Jani, R. Perera-Salazar, and M. McCulloch, 2021: Cooling for sustainable development. *Nature Sustainability*, **4** (3), 201–208. https://doi.org/10.1038/s41893-020-00627-w

241. Malik, A., C. Bongers, B. McBain, O. Rey-Lescure, R.d. Dear, A. Capon, M. Lenzen, and O. Jay, 2022: The potential for indoor fans to change air conditioning use while maintaining human thermal comfort during hot weather: An analysis of energy demand and associated greenhouse gas emissions. *The Lancet Planetary Health*, **6** (4), e301–e309. https://doi.org/10.1016/s2542-5196(22)00042-0

242. Prieto, A., U. Knaack, T. Auer, and T. Klein, 2018: Passive cooling & climate responsive façade design. *Energy and Buildings*, **175**, 30–47. https://doi.org/10.1016/j.enbuild.2018.06.016

243. Neumann, J.E., M. Amend, S. Anenberg, P.L. Kinney, M. Sarofim, J. Martinich, J. Lukens, J.-W. Xu, and H. Roman, 2021: Estimating $PM_{2.5}$-related premature mortality and morbidity associated with future wildfire emissions in the western US. *Environmental Research Letters*, **16** (3), 035019. https://doi.org/10.1088/1748-9326/abe82b

244. UNEP, 2022: Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires. A UNEP Rapid Response Assessment. United Nations Environment Programme, Nairobi, Kenya. https://www.unep.org/resources/report/spreading-wildfire-rising-threat-extraordinary-landscape-fires

245. Stone, S.L., L. Anderko, M.F. Berger, C.R. Butler, W.E. Cascio, and A. Clune, 2019: Wildfire Smoke: A Guide for Public Health Officials. EPA-452/R-21-901. U.S. Environmental Protection Agency. https://www.airnow.gov/sites/default/files/2021-09/wildfire-smoke-guide_0.pdf

246. Rappold, A.G., M.C. Hano, S. Prince, L. Wei, S.M. Huang, C. Baghdikian, B. Stearns, X. Gao, S. Hoshiko, W.E. Cascio, D. Diaz-Sanchez, and B. Hubbell, 2019: Smoke sense initiative leverages citizen science to address the growing wildfire-related public health problem. *GeoHealth*, **3** (12), 443–457. https://doi.org/10.1029/2019gh000199

247. Vaidyanathan, A., F. Yip, and P. Garbe, 2018: Developing an online tool for identifying at-risk populations to wildfire smoke hazards. *Science of The Total Environment*, **619–620**, 376–383. https://doi.org/10.1016/j.scitotenv.2017.10.270

248. Jones, R.T., T.H. Ant, M.M. Cameron, and J.G. Logan, 2021: Novel control strategies for mosquito-borne diseases. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **376** (1818), 20190802. https://doi.org/10.1098/rstb.2019.0802

249. Mafra-Neto, A. and T. Dekker, 2019: Novel odor-based strategies for integrated management of vectors of disease. *Current Opinion in Insect Science*, **34**, 105–111. https://doi.org/10.1016/j.cois.2019.05.007

250. Mwingira, V., L.E.G. Mboera, M. Dicke, and W. Takken, 2020: Exploiting the chemical ecology of mosquito oviposition behavior in mosquito surveillance and control: A review. *Journal of Vector Ecology*, **45** (2), 155–179. https://doi.org/10.1111/jvec.12387

251. Davis, C., A.K. Murphy, H. Bambrick, G.J. Devine, F.D. Frentiu, L. Yakob, X. Huang, Z. Li, W. Yang, G. Williams, and W. Hu, 2021: A regional suitable conditions index to forecast the impact of climate change on dengue vectorial capacity. *Environmental Research*, **195**, 110849. https://doi.org/10.1016/j.envres.2021.110849

252. Davis, J.K., G.P. Vincent, M.B. Hildreth, L. Kightlinger, C. Carlson, and M.C. Wimberly, 2018: Improving the prediction of arbovirus outbreaks: A comparison of climate-driven models for West Nile virus in an endemic region of the United States. *Acta Tropica*, **185**, 242–250. https://doi.org/10.1016/j.actatropica.2018.04.028

253. Muñoz, Á.G., X. Chourio, A. Rivière-Cinnamond, M.A. Diuk-Wasser, P.A. Kache, E.A. Mordecai, L. Harrington, and M.C. Thomson, 2020: *Ae*DES: A next-generation monitoring and forecasting system for environmental suitability of *Aedes*-borne disease transmission. *Scientific Reports*, **10** (1), 12640. https://doi.org/10.1038/s41598-020-69625-4

254. Peper, S.T., D.E. Dawson, N. Dacko, K. Athanasiou, J. Hunter, F. Loko, S. Almas, G.E. Sorensen, K.N. Urban, A.N. Wilson-Fallon, K.M. Haydett, H.S. Greenberg, A.G. Gibson, and S.M. Presley, 2018: Predictive modeling for West Nile virus and mosquito surveillance in Lubbock, Texas. *Journal of the American Mosquito Control Association*, **34** (1), 18–24. https://doi.org/10.2987/17-6714.1

255. Johnson, B.J., D. Brosch, A. Christiansen, E. Wells, M. Wells, A.F. Bhandoola, A. Milne, S. Garrison, and D.M. Fonseca, 2018: Neighbors help neighbors control urban mosquitoes. *Scientific Reports*, **8** (1), 15797. https://doi.org/10.1038/s41598-018-34161-9

256. Juarez, J.G., E. Carbajal, K.L. Dickinson, S. Garcia-Luna, N. Vuong, J.-P. Mutebi, R.R. Hemme, I. Badillo-Vargas, and G.L. Hamer, 2022: The unreachable doorbells of South Texas: Community engagement in *colonias* on the US-Mexico border for mosquito control. *BMC Public Health*, **22** (1), 1176. https://doi.org/10.1186/s12889-022-13426-z

257. Sanson, A.V., J. Van Hoorn, and S.E.L. Burke, 2019: Responding to the impacts of the climate crisis on children and youth. *Child Development Perspectives*, **13** (4), 201–207. https://doi.org/10.1111/cdep.12342

258. Marino, E., A. Jerolleman, and J. Maldonado, 2019: Law and policy for adaptation and relocation meeting: Summary report. *Meeting of the National Center for Atmospheric Research*, Boulder, CO. National Center for Atmospheric Research. https://risingvoices.ucar.edu/sites/default/files/Law%20%26%20Policy%20for%20Adaptation%20%26%20Relocation%20Meeting%20Summary%20Report.pdf

259. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

260. Maldonado, J., I.F.C. Wang, F. Eningowuk, L. Iaukea, A. Lascurain, H. Lazrus, C.A. Naquin, J.R. Naquin, K.M. Nogueras-Vidal, K. Peterson, I. Rivera-Collazo, M.K. Souza, M. Stege, and B. Thomas, 2021: Addressing the challenges of climate-driven community-led resettlement and site expansion: Knowledge sharing, storytelling, healing, and collaborative coalition building. *Journal of Environmental Studies and Sciences*, **11** (3), 294–304. https://doi.org/10.1007/s13412-021-00695-0

261. Adlam, C., D. Almendariz, R.W. Goode, D.J. Martinez, and B.R. Middleton, 2021: Keepers of the flame: Supporting the revitalization of Indigenous cultural burning. *Society & Natural Resources*, **35** (5), 1–16. https://doi.org/10.1080/08941920.2021.2006385

262. Redvers, N., 2021: The determinants of planetary health. *The Lancet Planetary Health*, **5** (3), e111–e112. https://doi.org/10.1016/s2542-5196(21)00008-5

263. Redvers, N., Y. Celidwen, C. Schultz, O. Horn, C. Githaiga, M. Vera, M. Perdrisat, L. Mad Plume, D. Kobei, M.C. Kain, A. Poelina, J.N. Rojas, and B.S. Blondin, 2022: The determinants of planetary health: An Indigenous consensus perspective. *The Lancet Planetary Health*, **6** (2), 156–163. https://doi.org/10.1016/s2542-5196(21)00354-5

264. Donatuto, J., L. Campbell, and R. Gregory, 2016: Developing responsive indicators of Indigenous community health. *International Journal of Environmental Research and Public Health*, **13** (9), 899. https://doi.org/10.3390/ijerph13090899

265. Donatuto, J., L. Campbell, and W. Trousdale, 2020: The "value" of values-driven data in identifying Indigenous health and climate change priorities. *Climatic Change*, **158** (2), 161–180. https://doi.org/10.1007/s10584-019-02596-2

266. Rice, J.L., D.A. Cohen, J. Long, and J.R. Jurjevich, 2020: Contradictions of the climate-friendly city: New perspectives on eco-gentrification and housing justice. *International Journal of Urban and Regional Research*, **44** (1), 145–165. https://doi.org/10.1111/1468-2427.12740

267. Rising Voices, 2022: Dialogues on centering justice in the National Climate Assessment. In: *Centering Justice and Weaving in a Diversity of Knowledges and Experiences Into the Fifth National Climate Assessment* (NCA5). 17 February 2022. National Center for Atmospheric Research. https://secasc.ncsu.edu/event/dialogues-on-centering-justice-in-the-national-climate-assessment/

268. Mallen, E., H.A. Joseph, M. McLaughlin, D.Q. English, C. Olmedo, M. Roach, C. Tirdea, J. Vargo, M. Wolff, and E. York, 2022: Overcoming barriers to successful climate and health Adaptation Practice: Notes from the field. *International Journal of Environmental Research and Public Health*, **19** (12), 7169. https://doi.org/10.3390/ijerph19127169

269. Romanello, M., C. Di Napoli, P. Drummond, C. Green, H. Kennard, P. Lampard, D. Scamman, N. Arnell, S. Ayeb-Karlsson, L.B. Ford, K. Belesova, K. Bowen, W. Cai, M. Callaghan, D. Campbell-Lendrum, J. Chambers, K.R. van Daalen, C. Dalin, N. Dasandi, S. Dasgupta, M. Davies, P. Dominguez-Salas, R. Dubrow, K.L. Ebi, M. Eckelman, P. Ekins, L.E. Escobar, L. Georgeson, H. Graham, S.H. Gunther, I. Hamilton, Y. Hang, R. Hänninen, S. Hartinger, K. He, J.J. Hess, S.-C. Hsu, S. Jankin, L. Jamart, O. Jay, I. Kelman, G. Kiesewetter, P. Kinney, T. Kjellstrom, D. Kniveton, J.K.W. Lee, B. Lemke, Y. Liu, Z. Liu, M. Lott, M.L. Batista, R. Lowe, F. MacGuire, M.O. Sewe, J. Martinez-Urtaza, M. Maslin, L. McAllister, A. McGushin, C. McMichael, Z. Mi, J. Milner, K. Minor, J.C. Minx, N. Mohajeri, M. Moradi-Lakeh, K. Morrissey, S. Munzert, K.A. Murray, T. Neville, M. Nilsson, N. Obradovich, M.B. O'Hare, T. Oreszczyn, M. Otto, F. Owfi, O. Pearman, M. Rabbaniha, E.J.Z. Robinson, J. Rocklöv, R.N. Salas, J.C. Semenza, J.D. Sherman, L. Shi, J. Shumake-Guillemot, G. Silbert, M. Sofiev, M. Springmann, J. Stowell, M. Tabatabaei, J. Taylor, J. Triñanes, F. Wagner, P. Wilkinson, M. Winning, M. Yglesias-González, S. Zhang, P. Gong, H. Montgomery, and A. Costello, 2022: The 2022 report of the *Lancet* Countdown on health and climate change: Health at the mercy of fossil fuels. *The Lancet*, **400** (10363), 1619–1654. https://doi.org/10.1016/s0140-6736(22)01540-9

270. Gaskin, C.J., D. Taylor, S. Kinnear, J. Mann, W. Hillman, and M. Moran, 2017: Factors associated with the climate change vulnerability and the adaptive capacity of people with disability: A systematic review. *Weather, Climate, and Society*, **9** (4), 801–814. https://doi.org/10.1175/wcas-d-16-0126.1

271. Stein, P.J.S., M.A. Stein, N. Groce, and M. Kett, 2023: The role of the scientific community in strengthening disability-inclusive climate resilience. *Nature Climate Change*, **13** (2), 108–109. https://doi.org/10.1038/s41558-022-01564-6

272. Krajeski, R., 2018: Framing research: Concepts and jargon in disaster research. In: *Natural Hazards Center Workshop*. Boulder, CO. Natural Hazards Center. https://hazards.colorado.edu/workshop/2018/session/framing-disaster-concepts-and-jargon-in-disaster-research

273. Peterson, K.J., 2020: Ch. 7. Sojourners in a new land: Hope and adaptive traditions. In: *Louisiana's Response to Extreme Weather: A Coastal State's Adaptation Challenges and Successes*. Laska, S., Ed. Springer, Cham, Switzerland, 185–214. https://doi.org/10.1007/978-3-030-27205-0_7

274. Rising Voices, 2019: Converging voices: Building relationships & practices for Intercultural science. In: *7th Annual Rising Voices Workshop*. Boulder, CO, 15–19 May 2019. National Center for Atmospheric Research. https://risingvoices.ucar.edu/sites/default/files/2021-11/RV7%20Workshop%20Report.pdf

275. Crimmins, A., J. Balbus, J.L. Gamble, D.R. Easterling, K.L. Ebi, J. Hess, K.E. Kunkel, D.M. Mills, and M.C. Sarofim, 2016: Appendix 1: Technical support document: Modeling future climate impacts on human health. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 287–300. https://doi.org/10.7930/j0kh0k83

276. EPA, 2023: How Climate Change Affects Human Health. U.S. Environmental Protection Agency. https://www.epa.gov/climateimpacts/climate-change-and-human-health#how

277. Dahl, K. and R. Licker, 2021: Too Hot to Work: Assessing the Threats Climate Change Poses to Outdoor Workers. Union of Concerned Scientists, Cambridge, MA. https://doi.org/10.47923/2021.14236

278. Cissé, G., R. McLeman, H. Adams, P. Aldunce, K. Bowen, D. Campbell-Lendrum, S. Clayton, K.L. Ebi, J. Hess, C. Huang, Q. Liu, G. McGregor, J. Semenza, and M.C. Tirado, 2022: Ch. 7. Health, wellbeing, and the changing structure of communities. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, 1041–1170. https://doi.org/10.1017/9781009325844.009

279. Dasgupta, S. and E.J.Z. Robinson, 2022: Attributing changes in food insecurity to a changing climate. *Scientific Reports*, **12** (1), 4709. https://doi.org/10.1038/s41598-022-08696-x

280. Ebi, K.L., N.H. Ogden, J.C. Semenza, and A. Woodward, 2017: Detecting and attributing health burdens to climate change. *Environmental Health Perspectives*, **125**, 085004. https://doi.org/10.1289/ehp1509

281. Mitchell, D., 2021: Climate attribution of heat mortality. *Nature Climate Change*, **11** (6), 467–468. https://doi.org/10.1038/s41558-021-01049-y

282. Ebi, K.L., 2022: Methods for quantifying, projecting, and managing the health risks of climate change. *NEJM Evidence*, **1** (8). https://doi.org/10.1056/evidra2200002

283. Couper, L.I., J.E. Farner, J.M. Caldwell, M.L. Childs, M.J. Harris, D.G. Kirk, N. Nova, M. Shocket, E.B. Skinner, L.H. Uricchio, M. Exposito-Alonso, and E.A. Mordecai, 2021: How will mosquitoes adapt to climate warming? *eLife*, **10**, e69630. https://doi.org/10.7554/elife.69630

284. Holeva-Eklund, W.M., S.J. Young, J. Will, N. Busser, J. Townsend, and C.M. Hepp, 2022: Species distribution modeling of *Aedes aegypti* in Maricopa County, Arizona from 2014 to 2020. *Frontiers in Environmental Science*, **10**, 1001190. https://doi.org/10.3389/fenvs.2022.1001190

285. Walker, K.R., D. Williamson, Y. Carrière, P.A. Reyes-Castro, S. Haenchen, M.H. Hayden, E. Jeffrey Gutierrez, and K.C. Ernst, 2018: Socioeconomic and human behavioral factors associated with *Aedes aegypti* (Diptera: Culicidae) immature habitat in Tucson, AZ. *Journal of Medical Entomology*, **55** (4), 955–963. https://doi.org/10.1093/jme/tjy011

286. Groenewold, M.R. and S.L. Baron, 2013: The proportion of work-related emergency department visits not expected to be paid by workers' compensation: Implications for occupational health surveillance, research, policy, and health equity. *Health Services Research*, **48** (6pt1), 1939–1959. https://doi.org/10.1111/1475-6773.12066

287. Shire, J., A. Vaidyanathan, M. Lackovic, and T. Bunn, 2020: Association between work-related hyperthermia emergency department visits and ambient heat in five southeastern states, 2010–2012—A case-crossover study. *GeoHealth*, **4** (8), 2019GH000241. https://doi.org/10.1029/2019gh000241

288. NIOSH, 2016: Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments. DHHS (NIOSH) Publication Number 2016–106. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Cincinnati, OH. https://www.cdc.gov/niosh/docs/2016-106/default.html

289. Delmelle, E.M., M.R. Desjardins, P. Jung, C. Owusu, Y. Lan, A. Hohl, and C. Dony, 2022: Uncertainty in geospatial health: Challenges and opportunities ahead. *Annals of Epidemiology*, **65**, 15–30. https://doi.org/10.1016/j.annepidem.2021.10.002

290. BLS, 2020: Survey of Occupational Injuries and Illnesses Data Quality Research. U.S. Bureau of Labor Statistics, accessed April 23, 2023. https://www.bls.gov/iif/data-quality-research/data-quality.htm

291. Michaels, D. and J. Barab, 2020: The Occupational Safety and Health Administration at 50: Protecting workers in a changing economy. *American Journal of Public Health*, **110** (5), 631–635. https://doi.org/10.2105/ajph.2020.305597

292. Adepoju, O.E., D. Han, M. Chae, K.L. Smith, L. Gilbert, S. Choudhury, and L. Woodard, 2021: Health disparities and climate change: The intersection of three disaster events on vulnerable communities in Houston, Texas. *International Journal of Environmental Research and Public Health*, **19** (1), 35. https://doi.org/10.3390/ijerph19010035

293. Busby, J.W., K. Baker, M.D. Bazilian, A.Q. Gilbert, E. Grubert, V. Rai, J.D. Rhods, S. Shidore, C.A. Smith, and M.E. Webber, 2021: Cascading risks: Understanding the 2021 winter blackout in Texas. *Energy Research & Social Science*, **77**, 102106. https://doi.org/10.1016/j.erss.2021.102106

294. Schiermeier, Q., 2021: Freak US winters linked to Arctic warming. *Nature*, **597** (7875), 165. https://doi.org/10.1038/d41586-021-02402-z

295. Gronlund, C.J., K.P. Sullivan, Y. Kefelegn, L. Cameron, and M.S. O'Neill, 2018: Climate change and temperature extremes: A review of heat- and cold-related morbidity and mortality concerns of municipalities. *Maturitas*, **114**, 54–59. https://doi.org/10.1016/j.maturitas.2018.06.002

296. Gupta, A., R. Soni, and M. Ganguli, 2021: Frostbite—Manifestation and mitigation. *Burns Open*, **5** (3), 96–103. https://doi.org/10.1016/j.burnso.2021.04.002

297. Son, J.-Y., J.C. Liu, and M.L. Bell, 2019: Temperature-related mortality: A systematic review and investigation of effect modifiers. *Environmental Research Letters*, **14** (7), 073004. https://doi.org/10.1088/1748-9326/ab1cdb

298. Cianconi, P., S. Betrò, and L. Janiri, 2020: The impact of climate change on mental health: A systematic descriptive review. *Frontiers in Psychiatry*, **11**, 74. https://doi.org/10.3389/fpsyt.2020.00074

299. National Academies of Sciences, Engineering, and Medicine, 2020: *A Framework for Assessing Mortality and Morbidity After Large-Scale Disasters*. MacKenzie, E.J., S.H. Wollek, O.C. Yost, and D.L. Cork, Eds. The National Academies Press, Washington, DC, 272 pp. https://doi.org/10.17226/25863

300. Marazzi, M., M. Boriana, and J.B. Gustavo, 2022: Mortality of Puerto Ricans in the USA post Hurricane Maria: An interrupted time series analysis. *BMJ Open*, **12** (8), e058315. https://doi.org/10.1136/bmjopen-2021-058315

301. Arendt, S., L. Rajagopal, C. Strohbehn, N. Stokes, J. Meyer, and S. Mandernach, 2013: Reporting of foodborne illness by U.S. consumers and healthcare professionals. *International Journal of Environmental Research and Public Health*, **10** (8), 3684–3714. https://doi.org/10.3390/ijerph10083684

302. Watts, N., M. Amann, N. Arnell, S. Ayeb-Karlsson, K. Belesova, M. Boykoff, P. Byass, W. Cai, D. Campbell-Lendrum, S. Capstick, J. Chambers, C. Dalin, M. Daly, N. Dasandi, M. Davies, P. Drummond, R. Dubrow, K.L. Ebi, M. Eckelman, P. Ekins, L.E. Escobar, L. Fernandez Montoya, L. Georgeson, H. Graham, P. Haggar, I. Hamilton, S. Hartinger, J. Hess, I. Kelman, G. Kiesewetter, T. Kjellstrom, D. Kniveton, B. Lemke, Y. Liu, M. Lott, R. Lowe, M.O. Sewe, J. Martinez-Urtaza, M. Maslin, L. McAllister, A. McGushin, S. Jankin Mikhaylov, J. Milner, M. Moradi-Lakeh, K. Morrissey, K. Murray, S. Munzert, M. Nilsson, T. Neville, T. Oreszczyn, F. Owfi, O. Pearman, D. Pencheon, D. Phung, S. Pye, R. Quinn, M. Rabbaniha, E. Robinson, J. Rocklöv, J.C. Semenza, J. Sherman, J. Shumake-Guillemot, M. Tabatabaei, J. Taylor, J. Trinanes, P. Wilkinson, A. Costello, P. Gong, and H. Montgomery, 2019: The 2019 report of The *Lancet* Countdown on health and climate change: Ensuring that the health of a child born today is not defined by a changing climate. *The Lancet*, **394** (10211), 1836–1878. https://doi.org/10.1016/s0140-6736(19)32596-6

303. EPA, 2023: Climate Change and Human Health: Who's Most at Risk? U.S. Environmental Protection Agency. https://www.epa.gov/climateimpacts/climate-change-and-human-health-whos-most-risk

304. Lee, D. and H.M. Murphy, 2020: Private wells and rural health: Groundwater contaminants of emerging concern. *Current Environmental Health Reports*, **7** (2), 129–139. https://doi.org/10.1007/s40572-020-00267-4

305. ERS, 2023: Food & Nutrition Assistance: Food Security in the U.S.—Key Statistics & Graphics. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-u-s/key-statistics-graphics/

306. Macdiarmid, J.I. and S. Whybrow, 2019: Nutrition from a climate change perspective. *Proceedings of the Nutrition Society*, **78** (3), 380–387. https://doi.org/10.1017/s0029665118002896

307. Zhang, R., X. Tang, J. Liu, M. Visbeck, H. Guo, V. Murray, C. McGillycuddy, B. Ke, G. Kalonji, P. Zhai, X. Shi, J. Lu, X. Zhou, H. Kan, Q. Han, Q. Ye, Y. Luo, J. Chen, W. Cai, H. Ouyang, R. Djalante, A. Baklanov, L. Ren, G. Brasseur, G.F. Gao, and L. Zhou, 2022: From concept to action: A united, holistic and One Health approach to respond to the climate change crisis. *Infectious Diseases of Poverty*, **11** (1), 17. https://doi.org/10.1186/s40249-022-00941-9

308. Roos, N., S. Kovats, S. Hajat, V. Filippi, M. Chersich, S. Luchters, F. Scorgie, B. Nakstad, O. Stephansson, and C. Consortium, 2021: Maternal and newborn health risks of climate change: A call for awareness and global action. *Acta Obstetricia et Gynecologica Scandinavica*, **100** (4), 566–570. https://doi.org/10.1111/aogs.14124

309. Smith, K.H., A.J. Tyre, J. Hamik, M.J. Hayes, Y. Zhou, and L. Dai, 2020: Using climate to explain and predict West Nile virus risk in Nebraska. *GeoHealth*, **4** (9), e2020GH000244. https://doi.org/10.1029/2020gh000244

310. Jodoin, S., A. Buettgen, N. Groce, P. Gurung, C. Kaiser, M. Kett, M. Keogh, S.S. Macanawai, Y. Muñoz, I. Powaseu, M.A. Stein, P.J.S. Stein, and E. Youssefian, 2023: Nothing about us without us: The urgent need for disability-inclusive climate research. *PLoS Climate*, **2** (3), e0000153. https://doi.org/10.1371/journal.pclm.0000153

311. Chakraborty, J., 2020: Unequal proximity to environmental pollution: An intersectional analysis of people with disabilities in Harris County, Texas. *The Professional Geographer*, **72** (4), 521–534. https://doi.org/10.1080/00330124.2020.1787181

312. Chakraborty, J., S.E. Grineski, and T.W. Collins, 2019: Hurricane Harvey and people with disabilities: Disproportionate exposure to flooding in Houston, Texas. *Social Science & Medicine*, **226**, 176–181. https://doi.org/10.1016/j.socscimed.2019.02.039

313. Dame-Griff, E.C., 2022: What do we mean when we say "Latinx?": Definitional power, the limits of inclusivity, and the (un/re)constitution of an identity category. *Journal of International and Intercultural Communication*, **15** (2), 119–131. https://doi.org/10.1080/17513057.2021.1901957

314. Borrell, L.N. and S.E. Echeverria, 2022: The use of Latinx in public health research when referencing Hispanic or Latino populations. *Social Science & Medicine*, **302**, 114977. https://doi.org/10.1016/j.socscimed.2022.114977

315. María del Río-González, A., 2021: To Latinx or not to Latinx: A question of gender inclusivity versus gender neutrality. *American Journal of Public Health*, **111** (6), 1018–1021. https://doi.org/10.2105/ajph.2021.306238

316. Anderson, H., C. Brown, L.L. Cameron, M. Christenson, K.C. Conlon, S. Dorevitch, J. Dumas, M. Eidson, A. Ferguson, E. Grossman, A. Hanson, J.J. Hess, B. Hoppe, J. Horton, M. Jagger, S. Krueger, T.W. Largo, G.M. Losurdo, S.R. Mack, C. Moran, C. Mutnansky, K. Raab, S. Saha, P.J. Schramm, A. Shipp-Hilts, S.J. Smith, M. Thelen, L. Thie, and R. Walker, 2017: Climate and Health Intervention Assessment: Evidence on Public Health Interventions to Prevent the Negative Health Effects of Climate Change. Centers for Disease Control and Prevention, Climate and Health Program, Atlanta, GA. https://www.cdc.gov/climateandhealth/docs/climateandhealthinterventionassessment_508.pdf

317. Abbinett, J., P.J. Schramm, S. Widerynski, S. Saha, S. Beavers, M. Eaglin, U. Lei, S.G. Nayak, M. Roach, M. Wolff, K.C. Conlon, and L. Thie, 2020: Heat Response Plans: Summary of Evidence and Strategies for Collaboration and Implementation. Centers for Disease Control and Prevention, National Center for Environmental Health. https://stacks.cdc.gov/view/cdc/93705

318. EPA, 2023: Public Health Adaptation Strategies for Climate Change. U.S. Environmental Protection Agency. https://www.epa.gov/arc-x/public-health-adaptation-strategies-climate-change

319. Sharifi, A., M. Pathak, C. Joshi, and B.-J. He, 2021: A systematic review of the health co-benefits of urban climate change adaptation. *Sustainable Cities and Society*, **74**, 103190. https://doi.org/10.1016/j.scs.2021.103190

320. Saha, S., A. Vaidyanathan, F. Lo, C. Brown, and J.J. Hess, 2021: Short term physician visits and medication prescriptions for allergic disease associated with seasonal tree, grass, and weed pollen exposure across the United States. *Environmental Health*, **20** (1), 85. https://doi.org/10.1186/s12940-021-00766-3

321. Schramm, P.J., C.L. Brown, S. Saha, K.C. Conlon, A.P. Manangan, J.E. Bell, and J.J. Hess, 2021: A systematic review of the effects of temperature and precipitation on pollen concentrations and season timing, and implications for human health. *International Journal of Biometeorology*, **65** (10), 1615–1628. https://doi.org/10.1007/s00484-021-02128-7

322. Hall, J., F. Lo, S. Saha, A. Vaidyanathan, and J. Hess, 2020: Internet searches offer insight into early-season pollen patterns in observation-free zones. *Scientific Reports*, **10** (1), 11334. https://doi.org/10.1038/s41598-020-68095-y

323. Stein, Z., 2021: Syndromic surveillance for monitoring health impacts of pollen exposure. In: *American Public Health Association Annual Meeting and Expo*. Atlanta, GA. https://apha.confex.com/apha/2021/meetingapi.cgi/Paper/510876?filename=2021_Abstract510876.pdf&template=Word

324. Aldrich, D.P. and M.A. Meyer, 2014: Social capital and community resilience. *American Behavioral Scientist*, **59** (2), 254–269. https://doi.org/10.1177/0002764214550299

325. Leiserowitz, A., E. Maibach, S. Rosenthal, and J. Kotcher, 2023: Climate Change in the American Mind: Politics & Policy. Yale Program on Climate Change Communication. https://policycommons.net/artifacts/3413332/politics-policy-december-2022/4212751/

326. Limaye, V.S., W. Max, J. Constible, and K. Knowlton, 2020: Estimating the costs of inaction and the economic benefits of addressing the health harms of climate change. *Health Affairs*, **39** (12), 2098–2104. https://doi.org/10.1377/hlthaff.2020.01109

327. Goshua, A., J. Gomez, B. Erny, M. Burke, S. Luby, S. Sokolow, A.D. LaBeaud, P. Auerbach, M.A. Gisondi, and K. Nadeau, 2021: Addressing climate change and its effects on human health: A call to action for medical schools. *Academic Medicine*, **96** (3), 324–328. https://doi.org/10.1097/acm.0000000000003861

328. Shea, B., K. Knowlton, and J. Shaman, 2020: Assessment of climate-health curricula at international health professions schools. JAMA *Network Open*, **3** (5), e206609. https://doi.org/10.1001/jamanetworkopen.2020.6609

329. Errett, N.A., K. Dolan, C. Hartwell, J. Vickery, and J.J. Hess, 2022: Adapting by their bootstraps: State and territorial public health agencies struggle to meet the mounting challenge of climate change. *American Journal of Public Health*, **112** (10), 1379–1381. https://doi.org/10.2105/ajph.2022.307038

330. University of Washington, 2023: What is Implementation Science? [Webpage], accessed May 25, 2023. https://impsciuw.org/implementation-science/learn/implementation-science-overview/

Fifth National Climate Assessment: Chapter 16

# Tribes and Indigenous Peoples

# Chapter 16. Tribes and Indigenous Peoples

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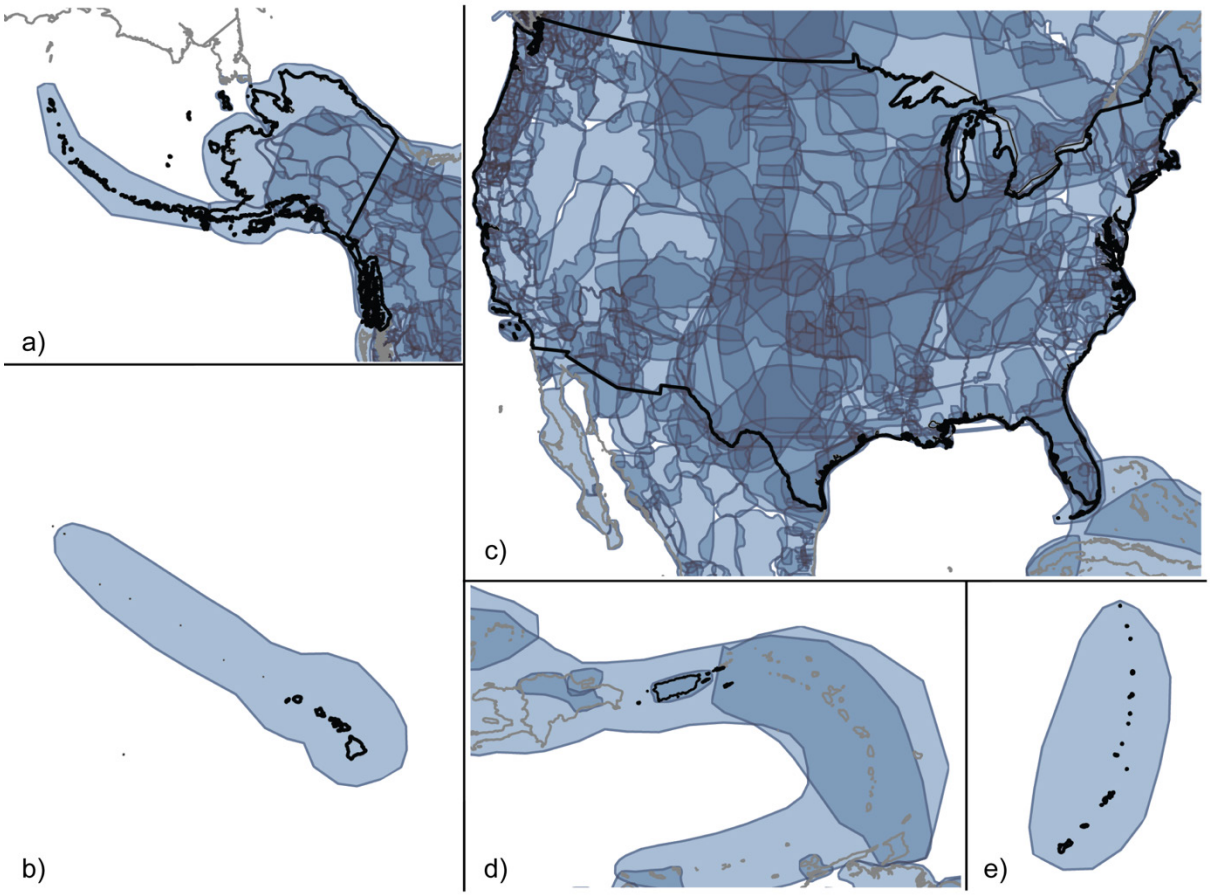
# Introduction

Indigenous Peoples in the United States represent more than 700 communities and Tribal Nations. They are culturally and politically unique and self-determining societies in North America, Hawai‘i, American Sāmoa, Guam, the Northern Mariana Islands, Puerto Rico, and the US Virgin Islands (Figure 16.1), encompassing diverse ecosystems. They differ in their relationships with federal, state, territorial, and local governments but have similarly endured genocide and land dispossession (Figure 16.2). Indigenous Peoples' origins begin millennia ago, long before the United States. Many Indigenous persons are scientists of the environment, holding holistic understandings of the interconnected drivers of climate change and evidence of climate-related changes and strategies for adaptation (Figure 16.3; KMs 26.1, 27.6, 30.2, 30.5).[1,2,3,4,5,6] For generations, Indigenous Peoples have centered their knowledge of climate change in their cultures, political organizations, and arts. Many Indigenous persons closely track natural cycles and assemblages of plants and animals, making them keenly aware of environmental disruptions.

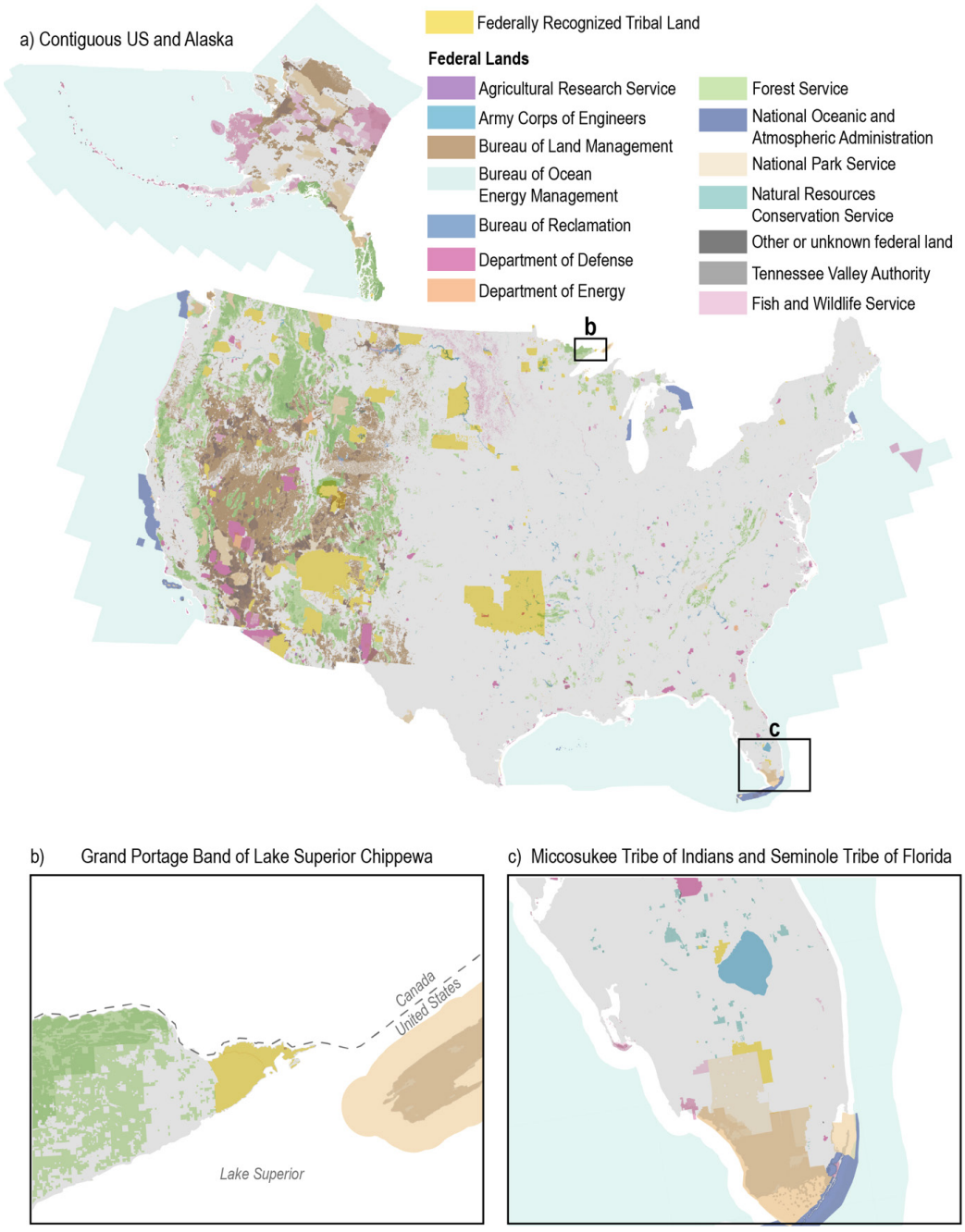
## Representative Locations of Indigenous Peoples




**Homelands of Indigenous Peoples are located throughout the US and its territories.**

**Figure 16.1.** The maps show pre–United States customary (traditional) homelands and some US-recognized contemporary homelands. The maps represent overlapping territories (approximately represented in outlined, shaded areas, with darker shading representing areas of overlap) in North America (**a** and **c**), Hawai‘i (**b**), Puerto Rico and the US Virgin Islands (**d**), and Guam and the Northern Mariana Islands (**e**). The maps exclude most Indigenous marine territories. Given available data, the maps omit many territories (e.g., in American Sāmoa). Figure credit: Colorado State University, NOAA NCEI, and CISESS NC.

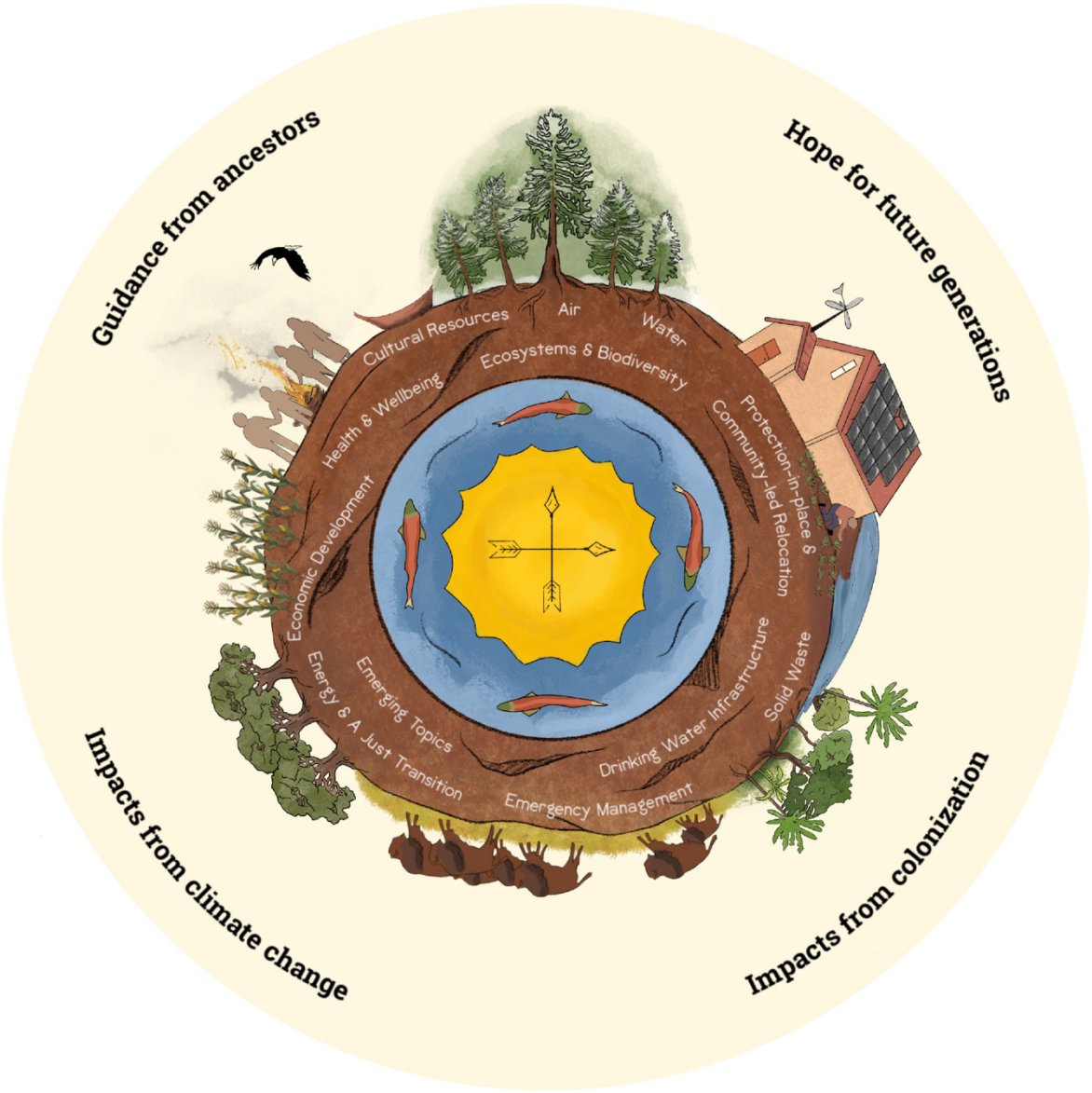
## The Complexity of Land Tenure for Indigenous People




**Federally Recognized Tribal Lands are often near federal lands, where Indigenous Peoples may have consultation, treaty, or comanagement rights.**

**Figure 16.2.** The maps show many of the current federally recognized reservations in the continental US, including Tribal trust lands (and excluding fee lands and Hawai'i, US Caribbean, and US-Affiliated Pacific Islands). Federal lands, including national parks, national forests, and wilderness areas, are shown, as Tribal Nations can have rights to comanage, exercise treaty rights, and consult on land management decisions. Panels (**a**), (**b**) and (**c**) show, in additional detail, the relationship between federal and Tribal lands. The profiles of (b) Grand Portage Band of Lake Superior Chippewa and (c) Miccosukee Tribe of Indians and Seminole Tribe of Florida highlight current and potential comanagement agreements between Federally Recognized Tribes and the Federal Government.[7,8] Figure credit: Citizen Potawatomi Nation, University of Minnesota, and DOI. See figure metadata for additional contributors.

## Indigenous Holistic Worldview




**Indigenous holistic worldviews offer diverse and complex expressions of climate change.**

**Figure 16.3.** As an intentionally non-exhaustive example by particular Indigenous designers, the "Indigenous holistic worldview" image demonstrates interconnected drivers of sustenance, climate change impacts, and future aspirations. Illustrations connecting human social systems and the environment, including the relationship between social justice (e.g., colonialism, racism) and environmental change (e.g., ecological degradation, pollution), represent certain Indigenous approaches to climate change. Figure credit: ©STACCWG 2021.[6] Used with permission.

Indigenous Peoples have distinct rights to self-determination, cultural protection, and land use in relation to federal, state, and local government and nonprofit and for-profit institutions.[6] For example, Alaska Native corporations own and hold resource rights in one-tenth of Alaska lands for the purpose of economic development.[9,10] Alaska Tribal governments are responsible for managing government services, including cultural revitalization, for their members yet control significantly less land than corporations (see Ch. 29). Broadly, Indigenous-operated institutions include local customary and traditional governing systems, US Federally Recognized Tribes, treaty organizations, Alaska Native Corporations, Alaska Native villages, community development corporations and financial institutions, Native Hawaiian Organizations and

Hawaiian Home Lands, Indigenous-serving organizations within US territories, state-recognized Tribes, urban Indigenous centers, and more.

US federal and some state governments have agencies and programs with legal mandates to support Indigenous Peoples' health, economic vitality, education, environmental quality, and cultural continuance. The Federal Government has a legal obligation to consult with Federally Recognized Tribes and the Native Hawaiian community.[11,12,13,14] The US has given a non-binding endorsement of Indigenous Peoples' rights as articulated in the United Nations Declaration on the Rights of Indigenous Peoples, which affirms that Indigenous Peoples have rights to self-determination and free prior and informed consent regarding territorial development and the protection of their health, cultures, and knowledge.

Climate change negatively disrupts Indigenous Peoples' health (KM 15.2), economic vitality, education, environmental quality, governance, and cultural continuance (Figure 16.3).[6,15] Historical abuses of Indigenous rights have significant responsibility for the heightened severity of climate disruption.[6,16,17] The US government's taking of land from Indigenous Peoples has increased vulnerability to climate disruption.[18,19,20] The growth of the US industrial sector heavily polluted and degraded Indigenous territories through mining, fossil-fuel energy development and use, commodity and plantation agriculture, unsustainable forestry, and military infrastructure and activities.[21,22,23,24,25,26,27]

Today, Indigenous initiatives addressing climate and energy are often organized as movements for protecting and advancing Indigenous rights. These include rights to self-determination regarding climate change responses in their territories—rights that are critical to Indigenous efforts to choose the best pathways for supporting health, economic vitality, educational institutions, environmental quality, governance, cultural continuance, and spiritual traditions.

## Key Message 16.1

## Indigenous Peoples Face Risks to Well-Being and Livelihoods from Climate Change and Barriers to Energy Sovereignty

Climate change continues to cause negative effects on critical aspects of Indigenous Peoples' well-being, including their livelihoods, health, nutrition, and cultural practices, as well as the ecological resilience of their territories (*very high confidence*). Indigenous Peoples are responding in diverse ways, including through energy sovereignty (*very high confidence*).

Indigenous Peoples face harms and risks from climate change that negatively affect their health and well-being, economic sustenance, and cultural integrity and continuity (KMs 15.3, 25.3, 27.6, 29.1).[28,29,30,31,32,33] Given the diversity of Indigenous Peoples, no single chapter could adequately address projections of the impacts of climate change on many hundreds of communities 25–100 years in the future. In this Key Message, relocation, including permanent relocation and managed retreat, is covered as a separate topic. Many Indigenous Peoples continue to be among the communities navigating climate-related disasters and negotiating permanent relocation, expansion, community-led relocation,[34] and managed retreat (KMs 29.1, 29.4, 30.2). Indigenous Peoples face injustice in energy transitions and barriers to investing in renewable energy.[35,36,37,38,39] The information in this Key Message builds on the findings of Tribal and Indigenous Peoples' chapters in previous National Climate Assessments without repeating previous findings.

## Indigenous Livelihoods and Economies

Indigenous livelihoods and economies often rely on combinations of subsistence systems, natural resource management, small businesses, nonprofit organizations, community development corporations and financial institutions, Tribal government employment and contracts, Tribal enterprises, and multinational corporations.[40] Regarding US indicators, Indigenous Peoples are disadvantaged in terms of income, employment, wealth, and access to adequate infrastructure, which has negative impacts on the availability of resources for climate response.[6,18] Despite disadvantages, Tribes manage complex governments and economies. For example, there are 87 Native American financial institutions (banks, credit unions, and loan funds) managing $8 billion (in 2022 dollars).[41]

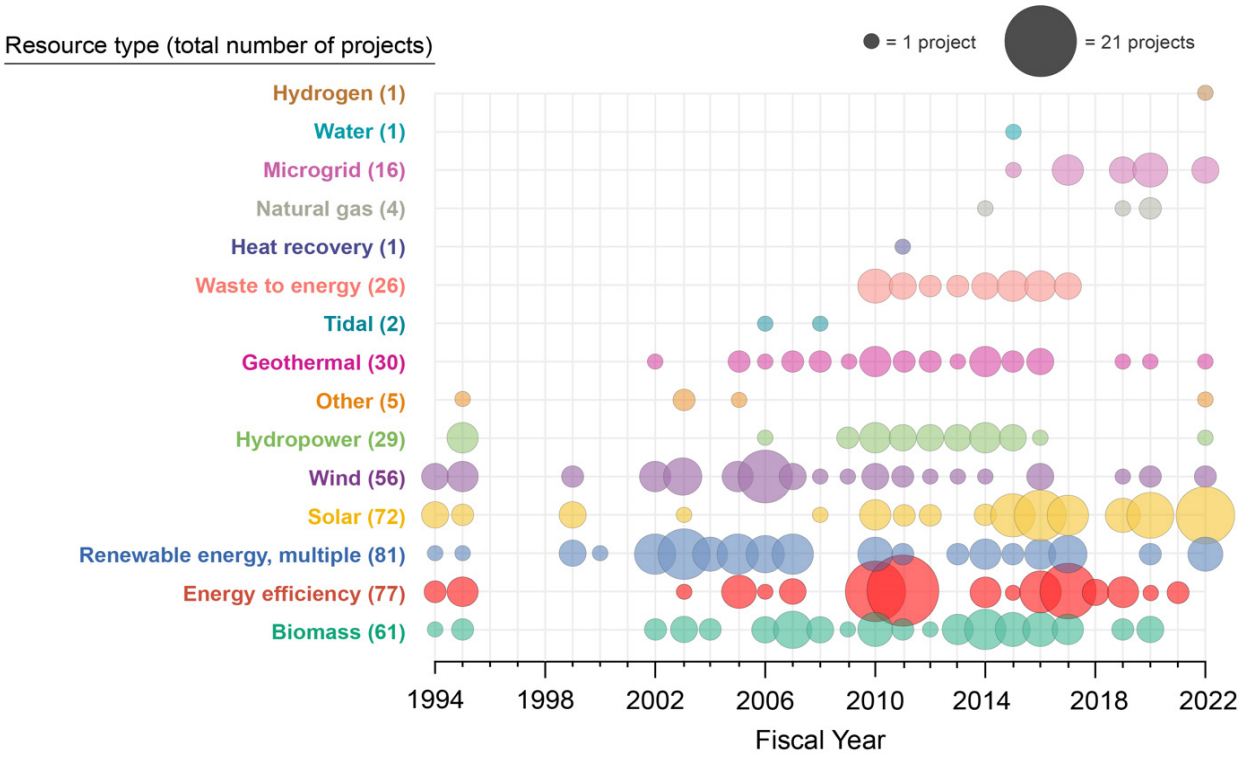
Climate change threatens to disrupt the conditions for critical Indigenous subsistence practices, including, but not limited to, planting, pollination, harvesting, the preparation and storage of food and medicines (i.e., medicinal plants), and subsistence-related travel (KMs 7.2, 10.2, 11.2, 21.3, 24.3, 29.3, 29.4, 29.5, 30.1, 30.2).[15,42,43,44,45,46,47,48,49,50,51,52,53,54] Other climate-induced economic disruptions to subsistence and business include losses of timber revenue from wildfire or declines in culturally important species used for activities like basketry,[55] berry harvesting,[56] fisheries,[57,58] and tourism (KMs 29.3, 30.3). Losses of subsistence lifestyles are associated with decreased capacity to cope with climate change.[59] Economic insecurity on subsistence and business can compound existing economic challenges,[60] including poverty, labor exploitation, colonial debts, and inaccessibility of finance mechanisms.[61,62,63]

Nonetheless, robust Indigenous economies and entrepreneurial enterprises provide paths toward greater Indigenous resilience. Revitalization of Indigenous agricultural practices are also linked to increased economic resilience and food security, such as Native Hawaiian loʻi and dryland agriculture.[64] In other cases, Indigenous People with strong ties to or ownership of successful and diverse economic enterprises have shown progress in their climate resilience.[65,66]

## Indigenous Energy

Lack of capacity to transition toward renewable energy can be considered a vulnerability to climate change—that is, vulnerability to being excluded from unlocking the capacity to enact mitigation measures. Numerous factors affect Indigenous self-determination in renewable energy, including barriers to infrastructure ownership, access to financing and tax incentives, the navigation of regulations and jurisdictions, and income opportunities from renewables (KM 23.4).[39,67,68,69,70,71,72,73,74] Affordable renewable energy is often inaccessible to Indigenous households, inhibiting a just energy transition (Figure 16.4).[18,75,76,77,78]

## Tribal Renewable Energy Projects




**The breadth of project type and funding amounts have increased for federally funded renewable energy projects.**

**Figure 16.4.** The figure shows federally funded Tribal renewable energy and energy-efficiency projects between 1994 and 2022. The size of the circles indicates the number of projects: the larger the circle, the more projects of that energy type were funded that year. Historically, projects like retrofitting to improve energy efficiency, as well as renewable energy projects including solar, wind, and biomass, often received funding. The more recent trend toward microgrid and solar projects mirrors efforts to build Tribal energy sovereignty. Figure credit: DOI, NOAA NCEI, and CISESS NC.

## *Health Risks*

Indigenous concepts of health and well-being often remain closely tied to the health of the environment, waters, and more-than-human relatives that provide for subsistence and cultural needs (KMs 29.1, 30.2).[6,79,80] Climate change has decreased Indigenous Peoples' access to nutritious subsistence diets necessary for food sovereignty and security (KMs 21.4, 27.1, 28.3, 30.1)[47,49,50,81,82,83] and access to clean water (KMs 4.2, 30.1).[84] Climate change generally has had detrimental health impacts to Indigenous Peoples (KM 15.1).[85] Negative health outcomes and deaths have increased from extreme weather events, including heatwaves, flooding, changing ice conditions, hurricanes/typhoons, and wildfires (KMs 23.1, 30.2).[15,86] These negative health outcomes include post-traumatic stress disorder, anxiety, suicide, and other mental, spiritual, and social–emotional health challenges (KMs 15.1, 23.1, 29.1; Figure 29.3),[87,88,89] which can be exacerbated by intergenerational trauma[90] and breakdowns in family and community relationships.[85] These negative health impacts can amplify existing stressors on Indigenous health and well-being, including inadequate infrastructure, high rates of certain health conditions, high burdens of pollution, limited access to healthcare, water scarcity, poor sanitation, risks to occupational safety, and disproportionately high rates of environmental justice–related violence and human rights violations, many of which are especially burdensome for women (KM 4.3).[15,17,84,85,91,92,93,94]

Climate change and the COVID-19 pandemic have negatively affected Indigenous cultural, spiritual, physical, and mental health. In Alaska, pandemic-related travel restrictions limited food access, seasonal harvesting, and communal gatherings that maintain Indigenous Knowledge and practices around food systems, causing physical and mental health impacts.[95,96] High fuel prices and low salmon prices disrupted Indigenous businesses.[97] Broadly, food supply shortages and high costs during the pandemic compounded preexisting Indigenous food insecurities.[97,98,99,100] Preexisting water scarcity, such as in the Navajo Nation (KM 28.1),[101] Crow Agency, Montana,[85] and many Alaska Native communities (KM 29.1),[102] limited sanitation and hygiene practices and inhibited hydration and nutrition (KM 15.2).[101,103,104,105,106] During the peak periods of COVID-19 infection, disrupted stewardship and cultural activities included first salmon ceremonies,[97] canoe journeys,[99] wildfire response,[45] and Indigenous sports (e.g., stickball, lacrosse).[107] Some communities were able to engage in socially distanced and safe activities.[108] Climate change compounded preexisting inequities among Indigenous People who have low access to healthcare (KM 15.2)[85,109] and high risk of COVID-19 infection, hospitalization, and death.[110]

## Culture

Climate change compromises Indigenous territorial integrity, spiritual values and practices, and lifeways essential to cultural heritage and identity (KMs 6.1, 10.1, 23.1, 26.1, 30.5; Box 1.3).[6,15,29] Climate-induced coastal hazards such as sea level rise, floods, storm surge, and erosion threaten Indigenous cultural sites, including burial grounds, sacred sites, museums, and other cultural infrastructure.[111,112,113,114] Climate change increasingly threatens the sustainability of culturally significant tree species used for making lodges,[115] totem poles,[116] basketry,[117] and maple syrup and sugar,[118] among other examples. As culturally significant habitats shift out of Indigenous jurisdictions, challenges arise for treaty rights, Native Hawaiian homelands, and other access rights.[15,80] Linguistically, some Indigenous place names that reference local geographic features, animals, plants, and first foods no longer accurately describe environmental conditions or associations.[119] Changes to sea ice in Alaska will make certain environmental words in the Inupiaq dialect of Wales obsolete.[120,121,122] These altered conditions could lead to health and safety concerns and significant cultural impacts.[28,122] Phenological changes impact the timing of culturally significant patterns in nature (KM 8.2). For example, the Indigenous Phenology Network formed to understand phenological changes on Indigenous lands throughout the US.[123]

## Relocation

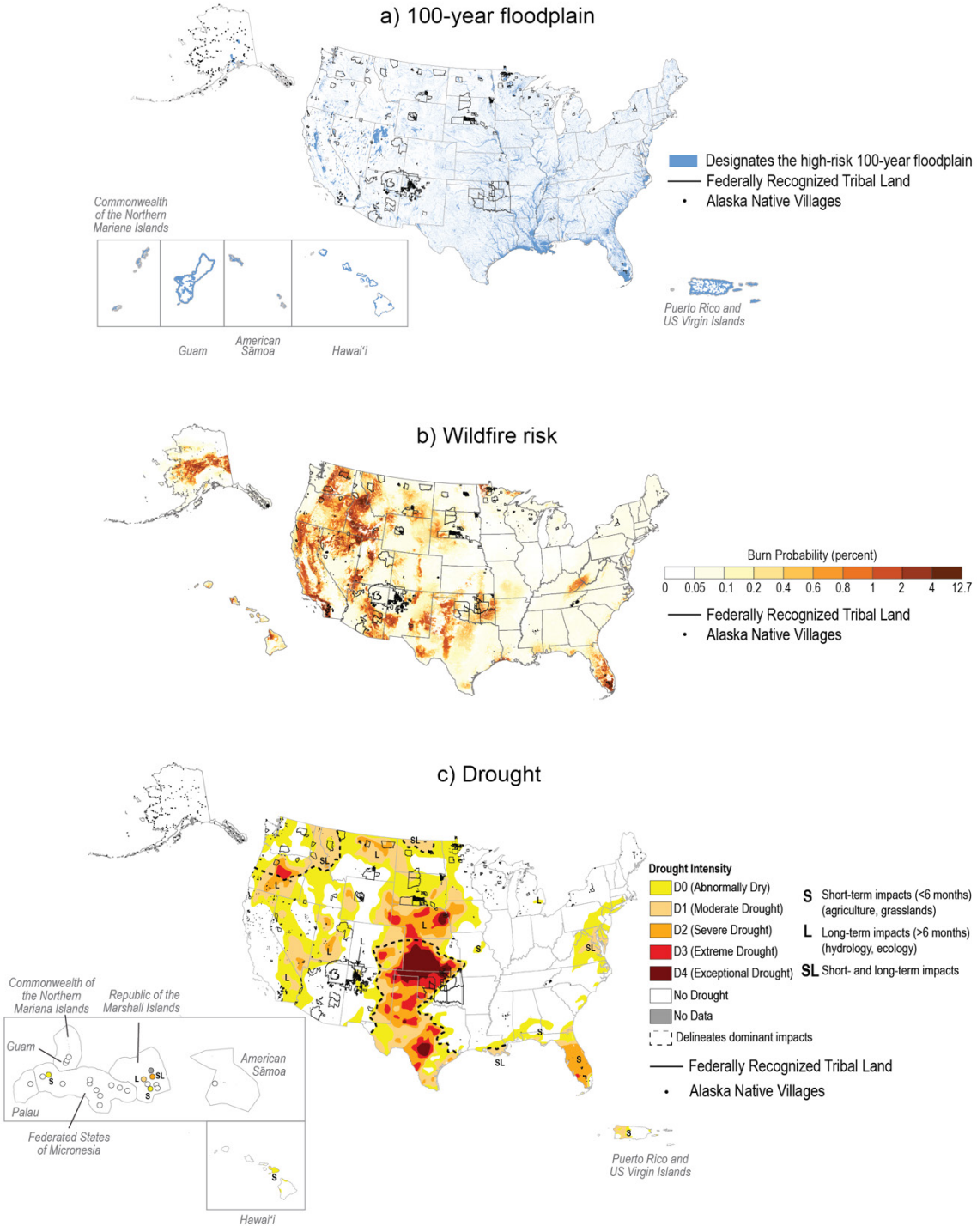
Indigenous Peoples, including Alaska Native villages, Pacific and Atlantic Coast Tribes, and Louisiana coastal Tribes, face unmet infrastructure needs and added stressors to culture and livelihoods as they relocate in response to increased erosion, more frequent flooding, increases in permafrost thaw, and rising sea levels (KM 29.2; Box 20.1).[18,114,124,125] Indigenous infrastructure is critical to supporting economies, sovereign security, and ways of life; it consists of a broad spectrum of human-built structures and facilities—from power grids to cultural and subsistence-related infrastructure—that are critical to the lives of Indigenous Peoples. According to the Bureau of Indian Affairs (BIA),[18] projected infrastructure costs arising from environmental impacts over the next 50 years are $4.8 billion for Alaska Native communities and a minimum of $2.1 billion for Federally Recognized Tribes (both amounts in 2022 dollars).[18] Seventy out of 200 Alaska Native villages face severe impacts from permafrost thaw, coastal erosion, and increased storminess.[126]

Indigenous Peoples in Hawai‘i, Puerto Rico, American Sāmoa, Guam, and the Commonwealth of the Northern Mariana Islands face distinct challenges for relocation based on their unique histories of colonialism. Often, impacts of climate change on US island regions and territories have been raised only in relation to impacts to life below water and not for Indigenous Peoples themselves.[127] Indigenous Peoples in US territories are often ineligible for federal funding for climate impacts, as well as international financing mechanisms due to their US affiliation.[128]

Most Indigenous Peoples face barriers to securing sufficient resources to implement climate adaptation, including home-building loans and complex technical data and training for decision-making (KMs 16.2, 29.4). Indigenous Peoples face intricate land policies that can prevent relocating or recovering their territorial bases, such as the US Supreme Court's decision in *Carcieri v. Salazar* (2009), which prohibited land restoration for certain Tribal Nations.[114,129,130,131,132]

When impacted by flooding, Indigenous Peoples do not receive equitable implementation of the National Flood Insurance Program (NFIP). The NFIP's inability to support a diversity of Indigenous jurisdictions and effectively communicate program information inhibits Indigenous Peoples' success as program operators and beneficiaries.[29] Indigenous Peoples face high costs through premiums, salaries for floodplain managers, and the expense of time and resources needed to develop, adopt, enforce, and maintain floodplain management ordinances.[133] They are required to pay into the NFIP even when they had been forcibly relocated by the US government to marginal, flood-prone land.[20,134,135,136] Indigenous Peoples are at risk of inundation and have limited ability to mitigate flood risk and manage floodplains, a circumstance made worse by the limits of available flood risk information. FEMA, EPA, and the US Army Corps of Engineers fund the development of flood-risk data (Figure 16.5a). However, historically inequitable and inconsistent delivery of data to Indigenous communities, including not honoring Tribal sovereignty, has prompted some Tribes to reject federally funded flood risk data and develop their own flood-risk data through university partnerships.[113,133]

## Publicly Available Climate Data in Relation to Indigenous Territories




**Some tribal lands are vulnerable to floods, wildfire, and drought.**

**Figure 16.5.** These maps feature (**a**) EPA and FEMA's 100-year floodplain projections; (**b**) wildfire hazard potential through burn probability, which is the annual probability of wildfire burning in a particular area, also known as wildfire likelihood; and (**c**) drought intensity and duration of impact. Federally Recognized Tribal Land is outlined in solid black lines, and Alaska Native villages are indicated by black dots. Wildfire risk data were not available for the US Caribbean and US-Affiliated Pacific Islands. Figure credits: (a, b) FEMA, NOAA NCEI, and CISESS NC; (c) adapted from US Drought Monitor 2023.[137]

## Key Message 16.2

## Self-Determination Is Key to Indigenous Peoples' Resilience to Climate Change

By exercising their right to self-determination, Indigenous Peoples can respond to climate change in ways that meet the needs and aspirations of their communities (*very high confidence*). However, their ability to exercise this right is often undermined by institutions and policies shaped by the impacts of settler colonialism (*very high confidence*). Expanded support from federal and state governments has the potential to uphold Indigenous rights to self-determination for guiding climate resilience (*high confidence*).

Self-determination means Indigenous Peoples make decisions about how to respond to climate change in ways that meet community-defined needs and aspirations. Indigenous climate resilience requires having adequate options for deciding how to adapt to and mitigate climate change and the capacity to implement decisions and make strategic revisions upon evaluation. For many Indigenous Peoples, certain social and political conditions can support or curtail their capacity for self-determination. Indigenous self-determination has been limited by institutions and policies, colonial in their organizational structure, that enable federal, state, and local governments and private industry to make decisions for Indigenous Peoples and to maintain low levels of funding and administrative support for implementation.[4,54,138,139,140,141,142] The ramifications are very practical in nature, including a lack of sufficient high-speed internet, adequate roads, shovel-ready projects, and financial, grant, and project management resources and staff.

### *Self-Determination*

Self-government is one application of self-determination. Although some Indigenous Peoples with self-government have rights recognized by the US, social and political conditions can curtail these rights.[138,143,144] Indigenous Peoples are often left out of cross-jurisdictional climate and emergency planning with federal, state, or local governments.[143] As an alternative, many Tribes have called for Indigenous-led management, as well as comanagement of lands, waters, and other resources currently under federal or state management. Comanagement, or even Indigenous-led management, represents opportunities to assert Tribal resource-management practices that address climate change.[145,146,147] Comanagement has been shown to be problematic if Indigenous capacities are not bolstered, communication is not clear and consistent, and Indigenous cultures are not uplifted.[148]

### *Consultation*

For Federally Recognized Tribes, the US has a duty of government-to-government consultation.[149] Consultative processes, however, are not yet widely practiced in ways that empower Tribes, even when the US and its agencies increase the number of consultations.[14,148] In some cases where federal or state agencies hire Tribal liaisons, the liaison role is only a small percentage of those employees' full-time positions, and they often are responsible for establishing and managing relationships with numerous Tribes.[150] Federal agencies must consult with the Native Hawaiian community in relation to certain statutes, and in some cases other Indigenous organizations, such as Native Hawaiian Organizations, can consult with federal agencies. Indigenous Peoples without formal consultative relationships face barriers to voicing their knowledge and concerns in public-participation and stakeholder-engagement processes, curtailing their self-determination.[151,152,153] Climate change issues involve coordination and communication that must be underwritten by consultation.

## Capacity Infrastructure

Indigenous Peoples can lack the needed staffing and workforce development capacities to fully implement climate change plans—efforts that can include applying for and managing grant funds, energy feasibility studies, natural resource assessments, hazard mitigation plans, environmental monitoring, legal efforts to enforce land, water and natural resource rights, and forest and natural resource protection and management (KM 23.5).[154] Funding is often not distributed in ways that Indigenous Peoples can access and benefit from, even during years when budget increases occur.[141] Funding may require matching funds, reimbursements, reporting requirements, degrees of shovel-readiness, or other administrative burdens that Indigenous administrative units cannot shoulder. This often results from lack of consultation of Indigenous Peoples in developing federal funding spending plans.[97,155] Tribal colleges and universities are often underfunded and face additional barriers to the accreditation necessary to train Indigenous community members in the academic fields related to climate change.[156]

Indigenous Peoples face compounding infrastructure deficiencies that threaten resilience—involving infrastructure tied to water quality and access, coastal shoreline protection, telecommunications and broadband, transportation, supply chain management, energy efficiency and access, and sustainable forest management (such as sawmills, secondary processing facilities, logging equipment, and staffing to operate and maintain infrastructure; KMs 23.4, 29.4, 30.3).[18,141] Indigenous Peoples face numerous barriers to accessing sufficient high-speed internet connections critical for education and capacity-building.[157,158] Coordinated infrastructure projects that mutually support one another would significantly advance Indigenous Peoples' resilience goals.[18] For example, Tribes have coordinated housing infrastructure programs with renewable energy projects[67] and community-level flood mitigation planning.[133,159] In Puerto Rico, community-coordinated efforts are working to serve energy and restoration needs (KM 23.5).[35,160]

## Indigenous Data for Governance

Indigenous Peoples face challenges in accessing relevant data to support decision-making for climate resilience.[6] For example, they lack environmental data for Tribal lands and waters and often have access only to data that are misaligned with community values and priorities.[161] Indigenous advocacy for data ownership, protection, and access focuses on relevance to their peoples, cultures, territories, ancestors, traditional places, knowledge, epidemiology, and public health.[162,163] This includes ensuring that other parties seeking to collect and use data from or relating to Indigenous Peoples follow the principle of free, prior, and informed consent. Indigenous Knowledge holders and leaders call for more equitable relationships with scientists and support for Indigenous-led research.[164] The CARE Principles (Collective benefit, Authority to control, Responsibility, and Ethics) for Indigenous Data Governance, which emphasize Indigenous concerns and rights about data, are increasingly being applied in climate change–related projects.[161,165,166,167,168] Large US-based environmental data repositories, including the Earth Science Information Partners, are currently exploring methods for operationalizing the CARE data principles by improving data management capacity to ensure that data can be disaggregated, scaled down, and used to support Indigenous climate change planning.[161,166,169,170]

## Indigenous Organizational Support

Indigenous organizations are important for carrying forward the messaging of their constituencies and providing additional unfulfilled services to communities. Indigenous urban centers provide large Indigenous populations in cities across the US—from New York to Los Angeles, Boston, Chicago, Phoenix, and more—with vital social services necessary for resilient urban populations in a changing climate (KM 12.4).[171] Inter-Tribal organizations and networks serve as resources for enhancing Tribes' climate change planning.[172,173] For example, the Intertribal Timber Council, Columbia River Inter-Tribal Fish Commission, and Great Lakes Indian Fish and Wildlife Commission are leading innovative climate adaptation research

in their regions and inspiring cross-cultural scientific collaborations with non-Indigenous researchers, scientists, and organizations.[144,174,175,176,177] Other organizations such as the National Congress of American Indians, United South and Eastern Tribes, and Affiliated Tribes of Northwest Indians support Tribes in their efforts to build climate resilience.[114,178,179] Indigenous businesses can provide climate services if offered equal access to contracts, opportunities, and information.[153] Indigenous organizations have sought to advocate for Indigenous perspectives, values, insights, and lived experiences of Indigenous Peoples by seeking to increase their access to appointed and elected leadership and decision-making positions.[180]

## Key Message 16.3

## Indigenous Leadership Guides Climate Change Response

Indigenous Peoples lead numerous actions that respond to climate change (*high confidence*). Indigenous-led organizations, initiatives, and movements have demonstrated diverse strategies for climate adaptation and mitigation that are guided by Indigenous Knowledges and values and by the pursuit of Indigenous rights (*high confidence*).

Indigenous-led actions to address climate and energy include implementation of climate adaptation strategies, climate and energy planning and policy initiatives, youth movements on climate justice, artistic mixed-media messaging about Indigenous experiences with and knowledges of climate change, and movements aimed to connect diverse Indigenous Peoples with one another spanning local to international scales (Figure 16.6).[6,80,138,181,182,183,184,185,186,187,188,189] Indigenous-led actions are often guided by Indigenous Knowledges, Indigenous values, and the pursuit of Indigenous rights to self-determination (Figure 16.3; KMs 2.3, 21.4, 24.4, 25.5, 26.3, 27.6, 28.3, 28.5, 29.7, 30.5).[190,191]

## Indigenous Ingenuity the Hopi Way

**Actions on climate change taken by the Hopi people engage science, tradition, and education.**

**Figure 16.6.** For more than 2,000 years, the Hopi have been adapting to an average of 6 to 10 inches of annual precipitation. Seeds from corn, beans, melons, and squash grown in drought years are used again in dry years. Hopi children learn dryland farming and the values, customs, and identities of why they farm. (**left**) Hopi soil-moisture conservation techniques allow corn plants to adapt to extreme conditions such as drought. (**bottom right**) Hopi children in a traditional corn field learn about science through a cultural lens. (**top right**) A traditional Hopi sandstone home incorporates Western science with the use of solar and hydro panels. Photo credits: © Michael K. Johnson, University of Arizona.

## *Indigenous-Led Climate Initiatives*

Many Tribes and Indigenous organizations have created climate plans. The Department of Energy has supported more than 190 Tribal-led energy projects, including many renewable energy projects (Figure 16.4). The BIA has funded many Tribal-led climate and energy projects, including 250 feasibility studies for renewable energy and hundreds of adaptation planning efforts (Tables 16.1, 16.2). Indigenous Peoples are including changing climate conditions in hazard mitigation plans (KMs 21.4, 25.2),[192] by incorporating available climate data (Figure 16.5), making them eligible for Hazard Mitigation Assistance grants through FEMA's Building Resilient Infrastructure and Communities program. Initiatives by the National Indian Health Board's Climate-Ready Tribes project, FEMA, the BIA's Tribal Climate Resilience program, the Tribal Climate Health Project, and the Institute for Tribal Environmental Professionals, among others (the Climate Adaptation Science Centers; the Climate Adaptation Knowledge Exchange, the Tribal Climate Change Project),[193] further capacities and expand funding.[159,194] The Institute for Tribal Environmental Professionals, for example, has created several levels of adaptation planning training, reaching more than 390 Tribes and more than 30 Tribal organizations.

**Table 16.1. Number of BIA Tribal Climate Resilience Funding Awards Per Category**

Cells with "n/a" for "not available" indicate years before an award category was offered. The categories include: 1, Trainings and Workshops; 2, Adaptation Planning; 3, Travel Support for Climate Adaptation Planning; 4, Ocean and Coastal Management Planning; 5, Travel Support for Ocean and Coastal Management; 6, Capacity Building for Scoping Efforts; 7, Relocation, Managed Retreat, or Protect-in-Place; 8, Internships; 9, Youth Engagement; 10, Implementation of Climate Adaptation Strategies; 11, Implementation of Community Relocation, Managed Retreat, or Protect-in-Place Actions; 12, Relocation, Managed Retreat, or Protect-in-Place Coordinator. Values indicate actual awarded amounts; no adjustments have been made for inflation. Funds for 2017 and 2018 were combined and awarded in 2018 due to delays resulting from governmental shutdown. Source: BIA.[195]

| Year | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 | Cat 8 | Cat 9 | Cat 10 | Cat 11 | Cat 12 | Total Awards | Total $ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | n/a | 6 | 9 | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | 15 | $327,637 |
| 2012 | n/a | 0 | 0 | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | 0 | $0 |
| 2013 | n/a | 6 | 13 | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | 19 | $694,731 |
| 2014 | 3 | 16 | 19 | n/a | 6 | n/a | n/a | n/a | n/a | n/a | n/a | n/a | 44 | $2,286,316 |
| 2015 | 8 | 38 | 30 | 19 | 7 | n/a | n/a | 12 | 7 | n/a | n/a | n/a | 121 | $13,322,972 |
| 2016 | 5 | 20 | 32 | 11 | 1 | 7 | n/a | 5 | 2 | n/a | n/a | n/a | 83 | $8,791,510 |
| 2017/18 | 18 | 42 | 32 | 30 | 13 | 3 | n/a | 0 | 0 | n/a | n/a | n/a | 138 | $12,410,810 |
| 2019 | 13 | 33 | 36 | 16 | 16 | 5 | n/a | 0 | 0 | n/a | n/a | n/a | 119 | $8,731,454 |
| 2020 | 15 | 49 | 41 | 14 | 12 | 13 | 15 | 0 | 0 | n/a | n/a | n/a | 159 | $14,462,186 |
| 2021 | 10 | 47 | 15 | 14 | 3 | 8 | 17 | 8 | 9 | n/a | n/a | n/a | 131 | $13,870,444 |
| 2022 | 8 | 26 | 10 | 10 | 4 | 3 | 11 | 5 | 6 | 17 | 6 | 12 | 118 | $44,628,511 |
| **Total** | **80** | **283** | **237** | **114** | **62** | **39** | **43** | **30** | **24** | **17** | **6** | **12** | **947** | **$119,526,571** |

**Table 16.2. Number of BIA Tribal Climate Resilience Funding Awards Per Region**

Awards made by the BIA Tribal Climate Resilience program to fund Tribal resilience actions. Source: BIA.[195]

| Year | Alaska | Eastern | Eastern Oklahoma | Great Plains | Midwest | Navajo | Northwest | Pacific | Rocky Mountain | Southern Plains | Southwest | Western | Total | Total $ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | 2 | 1 | 1 | 0 | 2 | 1 | 3 | 1 | 0 | 1 | 1 | 2 | 15 | $327,637 |
| 2012 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $0 |
| 2013 | 1 | 0 | 1 | 0 | 5 | 0 | 4 | 3 | 0 | 1 | 1 | 3 | 19 | $694,731 |
| 2014 | 7 | 2 | 4 | 3 | 6 | 0 | 8 | 9 | 1 | 3 | 0 | 1 | 44 | $2,286,316 |
| 2015 | 19 | 7 | 4 | 2 | 7 | 2 | 47 | 18 | 3 | 3 | 6 | 3 | 121 | $13,322,972 |
| 2016 | 15 | 2 | 3 | 2 | 3 | 2 | 33 | 14 | 1 | 5 | 1 | 2 | 83 | $8,791,510 |
| 2017/ 2018 | 44 | 6 | 5 | 2 | 5 | 1 | 45 | 9 | 5 | 4 | 6 | 6 | 138 | $12,410,810 |
| 2019 | 62 | 7 | 1 | 2 | 2 | 1 | 25 | 14 | 0 | 0 | 4 | 1 | 119 | $8,731,454 |
| 2020 | 62 | 11 | 5 | 4 | 6 | 0 | 29 | 24 | 2 | 7 | 4 | 5 | 159 | $14,462,186 |
| 2021 | 59 | 7 | 3 | 2 | 1 | 1 | 23 | 25 | 1 | 2 | 3 | 4 | 131 | $13,870,444 |
| 2022 | 43 | 2 | 4 | 2 | 4 | 1 | 30 | 16 | 5 | 3 | 1 | 7 | 118 | $44,628,511 |
| **Total** | **314** | **45** | **31** | **19** | **41** | **9** | **247** | **133** | **18** | **29** | **27** | **34** | **947** | **$119,526,571** |

Some planning processes deliberatively start with place-based Indigenous Knowledge. For example, some adaptation plans involve interviews with knowledge keepers to determine key ecological indicators for adaptation strategies, such as the restoration of fire-adapted ecosystems, cultural burning, and strategies for maintaining biodiverse crops and culturally important species and landscapes (KMs 21.4, 28.5).[6,80,87,196] In terms of values, some Tribal energy projects emphasize renewable energy as connected to elder care by lowering the cost of household energy for elders.[67] Indigenous-led planning processes can emphasize that rights to self-determination should govern decision-making about climate and energy.[6,38,197]

Climate change responses guided by Indigenous Knowledges and values include restoration efforts, food security initiatives (Boxes 30.3, 30.4), climate emergency response systems, and innovative communication mediums. Examples include the Tribal Climate Adaptation Menu[80] and Indigenous-supported efforts, such as those of the Karuk Tribe[198] to ensure that the State of California has permitting requirements for vegetation management to reduce fire hazards through prescribed burns that have cultural value. In 2021, the Onondaga Nation completed construction of the Tsha' Thoñswatha' firehouse and community hall, which is the Nation's first triple-net-zero (energy, water, and waste) emergency-management facility (Figure 16.7).[199]

## Tsha' Thoñswatha' Firehouse and Community Hall

**The Tsha' Thoñswatha' firehouse and community hall in the Onondaga Nation relies on renewable energy and meets a net-zero standard of energy use.**

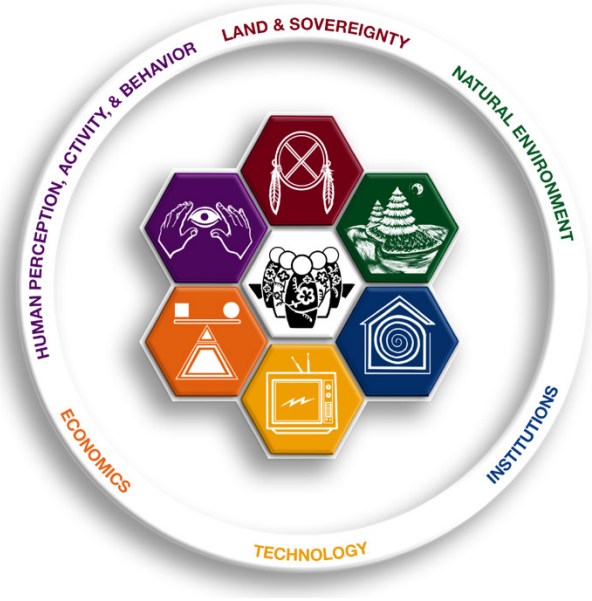
**Figure 16.7**. The firehouse was designed in collaboration with the community and reflects the Onondaga Nation's language and culture. Photo credits: © Kelsey Leonard, University of Waterloo.

There are many other examples of Indigenous Peoples' climate adaptation efforts. The College of Menominee Nation developed a community-engaged phenology research project to understand changes in plants on their reservation and also developed the culturally grounded Menominee Theoretical Model of Sustainability (Figure 16.8)[51,200] to guide research, education, and community engagement. Other efforts include Indigenous-led blue carbon ecosystem restoration, such as through kelp farming off the coasts of Long Island and Alaska (Focus on Blue Carbon). The Swinomish Indian Tribal Community of Washington, among others, is building clam gardens as a climate adaptation strategy to combat sea level rise and ocean acidification and to bolster food security.[201] Native Hawaiians are restoring their agricultural systems, given the ability of native species to adapt to the changing climate.[64] Land-based and culturally grounded healing initiatives support Indigenous communities' resilience.[17,202,203] Indigenous self-determination protects the capacities of Indigenous People to practice stewardship and caretaking relationships with their land.[204,205] Indigenous Knowledge and values guide strategies focused on traditional species and the significance of their ecological relationships, the revitalization of management practices that were suppressed by the US Government, the uplifting of Indigenous cultural practices as a way to motivate people to engage,[79,206] and the well-being of community members who face severe risks and negative impacts from climate change.[207]

## Climate Initiatives at College of Menominee Nation

a) Phenology station sign on the College of Menominee Nation campus

b) Menominee Theoretical Model of Sustainability




**At the College of Menominee Nation, Indigenous Knowledge guides climate change response.**

**Figure 16.8.** (**a**) The photo shows a phenology station sign at the College of Menominee Nation in Keshena, Wisconsin. The phenology project explores the effects of climate change on the reservation forest and community over time. The college has also developed the Menominee Theoretical Model of Sustainability (**b**), which guides climate change research, education, and community outreach and is an example of Indigenous leadership for climate adaptation. Photo credit: (a) © Thomas R. Kenote, College of Menominee Nation Sustainable Development Institute. Source: (b) The Menominee Theoretical Model of Sustainability (MTMS): 2021 Schwitzer Redesign—3D Version (adapted from Dockry et al. 2016[200]).

## *Youth-Led Climate Movements*

Youth-led movements (both US and international) continue to grow in number through the formation and engagement of organizations and coalitions, including the Climate Justice Alliance and the Indigenous Environmental Network, as well as through participation at the United Nations Framework Convention on Climate Change (UNFCCC) conferences of the parties (including the Paris Agreement).[208] The International Indigenous Youth Council was instrumental in leading the resistance against the proliferation of fossil fuel colonialism in Oceti Sakowin, historically known to some as the Sioux Nation.[209,210] Climate change was a key topic on the agenda at the February 2022 Native Youth Leadership Summit, held by The Youth Commission of the National Congress of American Indians.[211] Earth Ambassadors of United National Indian Tribal Youth Inc. have developed projects ranging from seed banking to waste management to address climate injustices facing their Indigenous communities.[212] Tribal colleges and universities are also engaged in building community resilience and supporting the next generation of climate leaders.[156,213,214,215] Another empowering youth-led initiative is Mni Ki Wakan, which is working towards Indigenous-led water justice for all.[216]

## *Art and Storytelling for Climate Communication*

Since time immemorial, Indigenous Peoples have shared Traditional Knowledges and historical context through arts and storytelling. In modern times, they are mobilizing innovative and diverse media, including visual and performance art,[217] film,[218,219] podcasts,[220] radio (www.nativenews.net), and other forms of story-

telling, to communicate firsthand experiences of climate impacts and adaptation initiatives for Indigenous lifeways. Indigenous approaches to communicating about climate change are integral to the expression of cultural lifeways, sharing culturally appropriate examples of climate adaptation, and discussing Indigenized approaches to climate planning.

## *Local, Inter-Tribal, and National Collaboration*

Indigenous Peoples' responses to climate change include collaborative environmental stewardship, protection, and coordination with other Tribes and Indigenous Peoples,[34] as well as with federal, state, and local governments, private organizations, and businesses (KM 12.4). In 2020 a collaborative Tribal-led nationwide effort was undertaken to review the Congressional Action Plan on the climate crisis[221] and to provide information, tools, and strategies for Tribal leaders to use in their advocacy on behalf of Indigenous Peoples.[18] For example, Tribes have coordinated with federal forests on regional fire management as a climate adaptation strategy.[6] Tribes and Indigenous Peoples continue to partner with each other to make unified statements and reports that can inform national and international climate policy and actions.[80,124,221] Inter-Tribal collaborations have engaged in regional monitoring of safety standards for shellfish and other resources.[6] Inter-Tribal consortia, such as the Midwest Tribal Energy Resources Association and the National Tribal Emergency Management Council, have fostered coordinated efforts to support the needs of individual Tribes. Indigenous nonprofit organizations, such as the NDN Collective, have produced funding programs and resources for Indigenous community-based organizations to access guidance and funds for renewable energy. Organizations such as the Indigenous Environmental Network have resisted the growth of the fossil fuel sector nationally.[222] Indigenous Peoples have participated in the conferences of parties of the UNFCCC (including the Paris Agreement), despite constraints to participation.[223] In 2019, the United Nations Educational, Scientific and Cultural Organization hosted a regional workshop titled "Mobilizing Indigenous and Local Knowledge Solutions: Addressing Climate Impacts and Vulnerabilities—A Perspective from the Caribbean Region," opening a dialogue and knowledge exchange across sectors, nations, and territories, including the US Caribbean.[191]

# Traceable Accounts

## *Process Description*

The authors of the Tribes and Indigenous Peoples chapter were selected based on their academic and government track records as experts on the topic of Indigenous Peoples and climate change in the US. Each author has a regional area of expertise in addition to expertise more broadly. The author team met virtually each week to discuss and cowrite the chapter. There was a weekly email update from the chapter lead (CL) to set the agenda for each weekly meeting five days in advance. The CL initiated discussion about the outline of each element of the chapter and received feedback from the chapter authors through email and through meetings. Revisions were made to the outline until agreement was achieved. The same process was initiated for the written content of the chapter and for each figure. After authors had contributed text, bibliographic references, and information and concepts pertaining to figures, the CL sought consensus through iterative communications over email and in meetings.

The Tribes and Indigenous Peoples chapter hosted one public meeting specifically on the chapter. The public comments from the meeting were reviewed and vetted for inclusion in the chapter. The chapter received comments from federal agencies, which the author team also responded to.

The author team has reviewed and included information from different types of credible sources relating to Indigenous Peoples and climate change. First, peer-reviewed scientific and academic literature on the topic was reviewed in its relationship to the US and its territories. Second, reports on the topic were reviewed if they met certain standards. They included the following: reports produced by Tribal governments, the US federal government, and state and local governments; reports produced by Indigenous organizations that have gone through a quality review process relevant to the particular information featured in the reports; and testimonies and eyewitness accounts by Indigenous People with climate change information. In cases where testimony and eyewitness accounts were used, appropriate recognition of the nature of the information was included in the Traceable Accounts.

Tribes and Indigenous Peoples in the US represent more than 700 communities and Tribal Nations that span the entire country and its territories. The communities encompass diverse regions and ecosystems. They differ culturally and have different relationships with the US, states, territories, and local governments. While different culturally, socially, and politically, Indigenous Peoples share comparable social circumstances. The circumstances include Indigenous Peoples' existence in what is now US territory prior to the establishment of the country; their distinct cultures; their having subsistence practices as a dimension of their economies, depending on the community or people; their living in lands today that are smaller than their ancestral land bases; and, depending on the community or people, their having endured environmental risks stemming from pollution and other environmental injustices, low investment in infrastructure by the US Government, and barriers to economic development. The social circumstances of Indigenous Peoples formed the basis of how the author team assessed information in this chapter. It is not possible to assess source material for more than 700 communities and peoples that are distinct ecologically, culturally, territorially, and politically. For this reason, the author team assessed as extensive a literature base as possible and drew on credible information to report information in the chapter that is relevant to the social circumstances of Indigenous Peoples. Throughout the chapter, the author team deliberately referenced Key Messages from other chapters relevant to Tribes and Indigenous Peoples; at the same time, the text is explicit that there is extreme differentiation across Indigenous Peoples.

## Key Message 16.1

# Indigenous Peoples Face Risks to Well-Being and Livelihoods from Climate Change and Barriers to Energy Sovereignty

### Description of Evidence Base

There is a diverse body of peer-reviewed academic literature, reports, testimony, and eyewitness accounts that disclose information about how Indigenous Peoples are impacted by climate change, including risks and current harms and costs. While climate change may present opportunities for certain populations, the current literature on this topic suggests strongly that Indigenous Peoples are currently facing increasing risks and burdensome harms and costs. The Fourth National Climate Assessment (NCA4)[224] reviewed literature since 2014 on this topic. NCA4 had three Key Messages in the Tribes and Indigenous Peoples chapter, focused on Indigenous Peoples facing risks, harms, and costs tied to their economies and cultures, their health, and their capacity to respond to disasters and natural hazards. This Assessment took into consideration the literature published since NCA4—from 2018 onward. Additional literature was found as well on topics not covered in NCA4, including energy systems and COVID-19. The Status of Tribes and Climate Change (STACC) Report[6] and the Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) were published in 2021 and 2022, respectively. Both include a thorough peer-reviewed assessment of climate change issues that Indigenous Peoples have faced in the context of the US since 2018. The two reports are comprehensive but not exhaustive of important climate change impacts that Indigenous Peoples face relating to climate and energy. There are approximately 460 million Indigenous Peoples throughout the world.

### Major Uncertainties and Research Gaps

For this topic, the author team had the capacity to analyze quality information covering numerous Tribes and Indigenous Peoples. However, the available literature does not come anywhere close to covering the total population of Tribes and Indigenous Peoples. As a result, there are hundreds of communities whose relationship to climate change is not covered in this chapter.

### Description of Confidence and Likelihood

*Very high confidence* is attributed to this Key Message for at least two reasons. First, one of the primary evidence bases being built on is the NCA. Since 2000, greater evidence has been analyzed about the vulnerability of Indigenous Peoples to climate change. NCA3 and NCA4 represented substantive advances in the documentation of this evidence. Since NCA4, other major scientific reports and empirically rigorous reports and technical contributions, including the reports of the IPCC[15] and the STACC Report,[6] have added further to the documented evidence. Second, scientists, Tribal staff, and nonprofit professionals have increased their publication of rigorous information on Indigenous vulnerability, and US Government agencies have advanced in their documentation of steps diverse Indigenous Peoples are taking to address climate change.

## Key Message 16.2

## Self-Determination Is Key to Indigenous Peoples' Resilience to Climate Change

### Description of Evidence Base

The evidence base is an assemblage of sources that range from documents produced by Indigenous Peoples themselves to academic literature. This diverse literature on the impacts of climate change and the responses of Indigenous Peoples to climate change discloses information about the conditions that affect Indigenous Peoples' options for adapting to and mitigating climate change. Domestic Policy Council (2021),[139] NCAI (2019b),[4] and the US Commission on Civil Rights (2018)[141] provide information about Indigenous capacities to exercise self-determination, including critical information about infrastructural, financial, and administrative capacities. Warner et al. (2020)[14] and Washburn (2021)[147] offer important information about how policies that support self-determination in the form of comanagement and nation-to-nation consultation are important strategies for responding to climate change and other environmental issues. The emerging literature on data governance is well documented in David-Chavez et al. (2019)[161] and Carroll et al. (2020).[165]

### Major Uncertainties and Research Gaps

Many of the conditions that create barriers for Indigenous Peoples in relation to climate change also affect other important areas, including political rights, education, health, and criminal justice. There continue to be gaps in research regarding how many total communities and peoples face particular climate challenges. However, some of the policies, governance mechanisms, and rights that are documented as barriers to Indigenous responsiveness to climate change pertain widely to Indigenous Peoples. There are also gaps in terms of being able to fully account for all of the adaptation and mitigation activities and processes that Indigenous Peoples are a part of or leading.

### Description of Confidence and Likelihood

*Very high confidence* is attributed to the statement that options for responding to climate change can be enhanced through support for self-determined decision-making. Within and beyond the available literature on climate change, the most common guidance from Indigenous and non-Indigenous sources is that Indigenous sovereignty, self-determination, and (where possible) self-governance are integral to supporting Indigenous efforts to address climate change. The author team discovered no literature claiming that US paternalism or domination of Indigenous Peoples is a pathway for mitigating climate risks and establishing renewable energy. *Very high confidence* is attributed to the statement that various institutions and related policy undermine or erode sovereignty and self-determination of Indigenous Peoples, negatively impacting opportunities for climate resilience. The literature, both since 2018 and before, depicts extensively and acutely the sources of barriers for Indigenous Peoples to address climate change and energy issues. There are no barriers that were discovered that operate independently of the influence of US colonialism on Indigenous Peoples. The final statement, on the relationship between federal and state support of Indigenous Peoples' self-determination, is assessed at *high confidence*. The available information and evidence demonstrate ways that such support can improve Indigenous self-determination; however, such improvements depend on how federal and state support is administered, such as avoiding measures that would foster problematic forms of dependence that would actually counteract the right to self-determination.

## Key Message 16.3

## Indigenous Leadership Guides Climate Change Response

### Description of Evidence Base

The evidence base includes some academic and scientific articles in addition to many reports from Indigenous Peoples on how they are responding to climate change. This Key Message is limited to describing known information about what Indigenous Peoples are doing in response to climate change. The reviewed literature, which is extensive, provides information on a topic area that is little represented in scientific assessments and provides information about climate change adaptation and mitigation measures that Indigenous Peoples have taken recently. In the NCA4 Tribe and Indigenous Peoples chapter,[29] the Bureau of Indian Affairs and the author team for that chapter created a graphic representation (Figure 15.1 in NCA4)[29] of actions that Indigenous Peoples have taken to respond to climate change. The chapter text itself did not devote a Key Message to describing the responses. That is, the chapter did not have focused treatment on the topic of how Indigenous Peoples are responding to climate change. The Key Message for the current chapter includes additions to the graphic, which is featured again in updated form. The author team searched extensively for cases of Indigenous responses to climate change, and this Key Message reflects the results of what the author team learned about the array of information and evidence. The STACC Report[6] provides dozens of small case studies of Indigenous Peoples' actions, and the Indigenous Environmental Network and Oil Change International report on mitigation provides cases of Indigenous advocacy against certain drivers of human-caused climate change.[222]

### Major Uncertainties and Research Gaps

Given that few climate change studies and scientific assessments take up and synthesize Tribal and Indigenous responses to climate change, this is one of the first assessments to describe the diverse array of responsive actions taking place. While the evidence base is extensive, there are certainly more responsive actions that Indigenous Peoples are engaged in that have not been published either at all or in a form that can be referenced in NCA. It is not known how many more cases there are. Indigenous Peoples, whether working through governments, organizations, or other entities, sometimes may not publish reports or publicly document the actions that they are taking. In other cases, documentation of an action may not be intended to be publicly referenced by its authors. And some publications, regardless of their quality, may not adhere with the requirements NCA has established for its evidence base.

### Description of Confidence and Likelihood

The Key Message attributes *high confidence* to the evidence that Indigenous Peoples are involved in diverse strategies for climate adaptation and mitigation and that Indigenous Knowledge, values, and rights shape many of the strategies. The literature on climate change demonstrates the importance of relevant and trusted leaders in orchestrating solutions that communities and staff will support. Indigenous leaders, Tribal governments, and Indigenous organizations have such relevance and potential for trustworthy leadership. Given that the legal, cultural, social, and political circumstances of Indigenous Peoples vary widely, the solutions that Indigenous Peoples are pursuing are unique in that they are tailored to such circumstances. There were no discovered instances where Indigenous Peoples' solutions were not so tailored.

# References


1. Kaholokula, J.K.A., S.K. Okamoto, and B.W.K. Yee, 2019: Special issue introduction: Advancing Native Hawaiian and other Pacific Islander health. *Asian American Journal of Psychology*, **10** (3), 197–205. https://doi.org/10.1037/aap0000167

2. Knopp, J.A., B. Levenstein, A. Watson, I. Ivanova, and J. Lento, 2022: Systematic review of documented Indigenous Knowledge of freshwater biodiversity in the circumpolar Arctic. *Freshwater Biology*, **67** (1), 194–209. https://doi.org/10.1111/fwb.13570

3. NCAI, 2019: Calling on the Department of Interior to Adopt Tribal Energy Resource Agreement Regulations That Respect Tribal Sovereignty and Self-Determination. Resolution #ABQ-19-032. National Congress of American Indians. https://www.ncai.org/attachments/resolution_kjpsfdqoiofcbwjkfcsdlfhgommyuyxetoshkgkdmwtxjuauceu_abq-19-032.pdf

4. NCAI, 2019: Tribal Nations and the United States. National Congress of American Indians, Washington, DC. https://www.ncai.org/about-tribes

5. Petzold, J., N. Andrews, J.D. Ford, C. Hedemann, and J.C. Postigo, 2020: Indigenous knowledge on climate change adaptation: A global evidence map of academic literature. *Environmental Research Letters*, **15** (11), 113007. https://doi.org/10.1088/1748-9326/abb330

6. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

7. Haaland, D. and T.J. Vilsack, 2021: Joint Secretarial Order on Fulfilling the Trust Responsibility to Indian Tribes in the Stewardship of Federal Lands and Waters. Joint Secretarial Order 3403. U.S. Department of Interior and U.S. Department of Agriculture, 5 pp. https://www.doi.gov/sites/doi.gov/files/elips/documents/so-3403-joint-secretarial-order-on-fulfilling-the-trust-responsibility-to-indian-tribes-in-the-stewardship-of-federal-lands-and-waters.pdf

8. Sams III, C.F., 2022: Tribal Co-Management of Federal Lands. U.S. Department of the Interior, Office of Congressional and Legislative Affairs, accessed May 23, 2023. https://www.doi.gov/ocl/tribal-co-management-federal-lands

9. ANCSA, n.d.: Overview of Entities Operating in the Twelve Regions. ANCSA Regional Association, Anchorage, AK, accessed July 18, 2023. https://ancsaregional.com/overview-of-entities/

10. Stewart, H., 2022: Sovereigns of no territory: Alaska Natives, ANCSA, and tribal self-determination. *Arizona Journal of Environmental Law & Policy*, **12** (3), 247–269. https://static1.squarespace.com/static/6307d452a995602a1c242475/t/63d8fc5aa339c47a5d56fe69/1675164762913/Sovereigns+of+No+Territory.pdf

11. Riley, J.K., C. Akamu, and L. Riley, 2023: Ēwe hānau o ka ʻāina: A policy review focused on Hawaiʻi's public land trust. *Land*, **12** (1). https://doi.org/10.3390/land12010048

12. Sproat, D.K., 2016: An Indigenous people's right to environmental self-determination: Native Hawaiians and the struggle against climate change devastation. *Stanford Environmental Law Journal*, **35** (2). https://law.stanford.edu/publications/an-indigenous-peoples-right-to-environmental-self-determination-native-hawaiians-and-the-struggle-against-climate-change-devastation/

13. The White House, 2021: Memorandum on Tribal Consultation and Strengthening Nation-to-Nation Relationships. The White House, Washington, DC, January 26, 2021. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/26/memorandum-on-tribal-consultation-and-strengthening-nation-to-nation-relationships/

14. Warner, E.K., K. Lynn, and K. Whyte, 2020: Changing consultation. *UCD Law Review*, **54**, 1127. https://lawreview.law.ucdavis.edu/issues/54/2/articles/files/54-2_warner_lynn_whyte.pdf

15. IPCC, 2022: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844

16. Chisholm Hatfield, S. and M.M. Dalton, 2020: Integrating Traditional Ecological Knowledge and Western Climate science to enhance climate resilience of tribal communities. In: *AGU Fall Meeting Abstracts*. American Geophysical Union. https://ui.adsabs.harvard.edu/abs/2020agufmsy027..07c

17. Ford, J.D., N. King, E.K. Galappaththi, T. Pearce, G. McDowell, and S.L. Harper, 2020: The resilience of Indigenous peoples to environmental change. *One Earth*, **2** (6), 532–543. https://doi.org/10.1016/j.oneear.2020.05.014

18. BIA, 2020: The Unmet Infrastructure Needs of Tribal Communities and Alaska Native Villages in Process of Relocating to Higher Ground as a Result of Climate Change. Department of Interior, Bureau of Indian Affairs, Albuquerque, NM. https://www.bia.gov/news/unmet-infrastructure-needs-tribal-communities-and-alaska-native-villages-process-relocation

19. Crepelle, A., 2018: Standing Rock in the swamp: Oil, the environment, and the United Houma Nation's struggle for federal recognition. *Loyola Law Review*, **64**, 141–186. https://dspace.loyno.edu/xmlui/handle/123456789/61

20. Farrell, J., P.B. Burow, K. McConnell, J. Bayham, K. Whyte, and G. Koss, 2021: Effects of land dispossession and forced migration on Indigenous peoples in North America. *Science*, **374** (6567), 4943. https://doi.org/10.1126/science.abe4943

21. Fixico, D.L., 2012: *The Invasion of Indian Country in the Twentieth Century American Capitalism and Tribal Natural Resources*, 2nd ed. University Press of Colorado, 278 pp. http://www.jstor.org/stable/j.ctt46nvt7

22. Frain, S.C., 2018: 'Make America Secure': Media, militarism, and climate change in the Marianas Archipelago. *Pacific Journalism Review*, **24** (2), 218–240. https://doi.org/10.24135/pjr.v24i2.407

23. Goodyear-Kaopua, N., I. Hussey, and E.K.A. Wright, Eds., 2014: *A Nation Rising: Hawaiian Movements for Life, Land, and Sovereignty*. Duke University Press, Durham, NC, 416 pp. https://www.dukeupress.edu/a-nation-rising

24. Kojola, E., 2019: Bringing back the mines and a way of life: Populism and the politics of extraction. *Annals of the American Association of Geographers*, **109** (2), 371–381. https://doi.org/10.1080/24694452.2018.1506695

25. Liboiron, M., 2021: *Pollution Is Colonialism*. Duke University Press, Durham, NC, 216 pp. https://www.dukeupress.edu/pollution-is-colonialism

26. Perez, C.S., 2021: Thinking (and feeling) with Anthropocene (Pacific) islands. *Dialogues in Human Geography*, **11** (3), 429–433. https://doi.org/10.1177/20438206211017453

27. Spencer, M.S., T. Fentress, A. Touch, and J. Hernandez, 2020: Environmental justice, Indigenous knowledge systems, and Native Hawaiians and other Pacific Islanders. *Human Biology*, **92** (1), 45–57. https://doi.org/10.13110/humanbiology.92.1.06

28. Bisbal, G.A. and C.E. Jones, 2019: Responses of Native American cultural heritage to changes in environmental setting. *AlterNative: An International Journal of Indigenous Peoples*, **15** (4), 359–367. https://doi.org/10.1177/1177180119847726

29. Jantarasami, L.C., R. Novak, R. Delgado, E. Marino, S. McNeeley, C. Narducci, J. Raymond-Yakoubian, L. Singletary, and K.P. Whyte, 2018: Ch. 15. Tribes and Indigenous Peoples. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program,, Washington, DC, USA, 572–603. https://doi.org/10.7930/nca4.2018.ch15

30. Marks-Marino, D., 2021: The Seminole Tribe of Florida. Northern Arizona University, Institute for Tribal Environmental Professionals, Climate Change Program. https://www7.nau.edu/itep/main/tcc/tribes/gc_seminole

31. Sharp, F., 2019: Quinault Indian Nation Testimony, United States House of Representatives Committee on Natural Resources, Subcommittee on Water, Oceans, and Wildlife. Quinault Indian Nation, 5 pp. https://www.congress.gov/116/meeting/house/109853/witnesses/HHRG-116-II13-Wstate-SharpF-20190725.pdf

32. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

33. Weiskopf, S.R., M.A. Rubenstein, L.G. Crozier, S. Gaichas, R. Griffis, J.E. Halofsky, K.J. Hyde, T.L. Morelli, J.T. Morisette, R.C. Muñoz, A.J. Pershing, D.L. Petersone, R. Poudel, M.D. Staudinger, A.E. Sutton-Grier, L. Thompson, J. Vose, J.F. Weltzin, and K.P. Whyte, 2020: Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, **733**, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782

34. Maldonado, J., D. Antrobus, C. Comardelle, S.R. Cox, L. Laukea, C. Jones, P. Keys, H. Mullen, M. Neale, and D. Sambo Dorough, 2021: Ch. 10. Protection-in-place & community-led relocation. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 241–259. http://nau.edu/stacc2021

35. de Onís, C.M., 2018: Energy colonialism powers the ongoing unnatural disaster in Puerto Rico. *Frontiers in Communication*, **3**, 2. https://doi.org/10.3389/fcomm.2018.00002

36. Kronk, E.A., 2009: Alternative energy development in Indian country: Lighting the way for the seventh generation. *Idaho Law Review*, **46** (2). http://ssrn.com/abstract=2146189

37. Lee, D., C. Schelly, V.S. Gagnon, S. Smith, and S. Tiwari, 2023: Preferences and perceived barriers to pursuing energy sovereignty and renewable energy: A tribal nations perspective. *Energy Research & Social Science*, **97**, 102967. https://doi.org/10.1016/j.erss.2023.102967

38. Sovacool, B.K., S.E. Bell, C. Daggett, C. Labuski, M. Lennon, L. Naylor, J. Klinger, K. Leonard, and J. Firestone, 2023: Pluralizing energy justice: Incorporating feminist, anti-racist, Indigenous, and postcolonial perspectives. *Energy Research & Social Science*, **97**, 102996. https://doi.org/10.1016/j.erss.2023.102996

39. Zimmerman, M.G. and T.G. Reames, 2021: Where the wind blows: Exploring barriers and opportunities to renewable energy development on United States tribal lands. *Energy Research & Social Science*, **72**, 101874. https://doi.org/10.1016/j.erss.2020.101874

40. Jorgensen, M. and J. Timeche, 2021: Ch. 7. Native America x rural America: Tribal nations as key players in regional rural economies. In: *Investing in Rural Prosperity*. Saint Louis Fed Eagle, Federal Reserve Bank of St. Louis. https://nni.arizona.edu/publications/native-america-x-rural-america-tribal-nations-key-players-regional-rural-economies

41. Kokodoko, M., 2022: Enhanced Tool Maps Critical Role of Native American Financial Institutions. Federal Reserve Bank of Minneapolis, Center for Indian Country Development. https://www.minneapolisfed.org/article/2022/enhanced-tool-maps-critical-role-of-native-american-financial-institutions

42. Angel, J., C. Swanson, B.M. Boustead, K.C. Conlon, K.R. Hall, J.L. Jorns, K.E. Kunkel, M.C. Lemos, B. Lofgren, T.A. Ontl, J. Posey, K. Stone, G. Takle, and D. Todey, 2018: Ch. 21. Midwest. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 872–940. https://doi.org/10.7930/nca4.2018.ch21

43. Cold, H.S., T.J. Brinkman, C.L. Brown, T.N. Hollingsworth, D.R.N. Brown, and K.M. Heeringa, 2020: Assessing vulnerability of subsistence travel to effects of environmental change in Interior Alaska. *Ecology and Society*, **25** (1). https://doi.org/10.5751/es-11426-250120

44. Dupigny-Giroux, L.A., E.L. Mecray, M.D. Lemcke-Stampone, G.A. Hodgkins, E.E. Lentz, K.E. Mills, E.D. Lane, R. Miller, D.Y. Hollinger, W.D. Solecki, G.A. Wellenius, P.E. Sheffield, A.B. MacDonald, and C. Caldwell, 2018: Ch. 18. Northeast. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 669–742. https://doi.org/10.7930/nca4.2018.ch18

45. Green, K.M., A.H. Beaudreau, M.H. Lukin, and L.B. Crowder, 2021: Climate change stressors and social-ecological factors mediating access to subsistence resources in Arctic Alaska. *Ecology and Society*, **26** (4). https://doi.org/10.5751/es-12783-260415

46. Herman-Mercer, N.M., M. Laituri, M. Massey, E. Matkin, R. Toohey, K. Elder, P.F. Schuster, and E. Mutter, 2019: Vulnerability of subsistence systems due to social and environmental change: A case study in the Yukon-Kuskokwim Delta, Alaska. *Arctic*, **72** (3), 215–335. https://doi.org/10.14430/arctic68867

47. ICC Alaska, 2020: Food Sovereignty and Self-Governance: Inuit Role in Managing Arctic Marine Resources. Inuit Circumpolar Council Alaska, Anchorage, AK. https://www.inuitcircumpolar.com/project/food-sovereignty-and-self-governance-inuit-role-in-managing-arctic-marine-resources/

48. Inuit Tapiriit Kanatami, 2019: National Inuit Climate Change Strategy. Inuit Tapiriit Kanatami. https://www.itk.ca/wp-content/uploads/2019/06/ITK_Climate-Change-Strategy_English.pdf

49. Kapp, A., 2019: Aroostook Band of Micmac Indians. Northern Arizona University, Institute for Tribal Environmental Professionals, 9 pp. https://www7.nau.edu/itep/main/tcc/tribes/ne_micmacs

50. Kapp, A., 2019: The La Jolla Band of Luiseño Indians, September, 2019. Northern Arizona University, Institute for Tribal Environmental Professionals, Climate Change Program, 3 pp. https://www7.nau.edu/itep/main/tcc/tribes/sw_lajolla

51. Kenote, T. 2020: Indigenous Phenology: An Interdisciplinary Case Study on Indigenous Phenological Knowledge on the Menominee Nation Forest. Master of Science, University of Minnesota Digital Conservancy, 91 pp. https://hdl.handle.net/11299/216076

52. Markon, C., S. Gray, M. Berman, L. Eerkes-Medrano, T. Hennessy, H. Huntington, J. Littell, M. McCammon, R. Thoman, and S. Trainor, 2018: Ch. 26. Alaska. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1185–1241. https://doi.org/10.7930/nca4.2018.ch26

53. May, K., C. Luce, J. Casola, M. Chang, J. Cuhaciyan, M. Dalton, S. Lowe, G. Morishima, P. Mote, A. Petersen, G. Roesch-McNally, and E. York, 2018: Ch. 24. Northwest. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1036–1100. https://doi.org/10.7930/nca4.2018.ch24

54. Ristroph, E.B., 2019: Avoiding maladaptations to flooding and erosion: A case study of Alaska Native villages. *Ocean and Coastal Law Journal*, **24** (2), 110–135. https://digitalcommons.mainelaw.maine.edu/oclj/vol24/iss2/2

55. Dockry, M.J. and S.J. Hoagland, 2017: A special issue of the *Journal of Forestry*—Tribal forest management: Innovations for sustainable forest management. *Journal of Forestry*, **115** (5), 339–340. https://doi.org/10.5849/jof-2017-040

56. Herman-Mercer, N.M., R.A. Loehman, R.C. Toohey, and C. Paniyak, 2020: Climate- and disturbance-driven changes in subsistence berries in coastal Alaska: Indigenous Knowledge to inform ecological inference. *Human Ecology*, **48** (1), 85–99. https://doi.org/10.1007/s10745-020-00138-4

57. Hedden-Nicey, D.R. and L.K. Caldwell, 2020: Indigenous rights and climate change: The influence of climate change on the quantification of reserved instream water rights for American Indian tribes. *Utah Law Review*, **2020** (3). https://doi.org/10.26054/0d-6t19-bfke

58. Kozich, A.T., V.S. Gagnon, G. Mensch, S. Michels, and N. Gehring, 2020: Walleye Ogaawag Spearing in the Portage waterway, Michigan: Integrating mixed methodology for insight on an important tribal fishery. *Journal of Contemporary Water Research & Education*, **169** (1), 101–116. https://doi.org/10.1111/j.1936-704x.2020.03335.x

59. McMillen, H., T. Ticktin, and H.K. Springer, 2017: The future is behind us: Traditional ecological knowledge and resilience over time on Hawai'i Island. *Regional Environmental Change*, **17** (2), 579–592. https://doi.org/10.1007/s10113-016-1032-1

60. Allard, M.D. and V. Brundage Jr., 2019: American Indians and Alaska Natives in the U.S. Labor Force. U.S. Department of Labor, U.S. Bureau of Labor Statistics. https://www.bls.gov/opub/mlr/2019/article/american-indians-and-alaska-natives-in-the-u-s-labor-force.htm

61. Garriga-López, A.M., 2020: Debt, crisis, and resurgence in Puerto Rico. *Small Axe: A Caribbean Journal of Criticism*, **24** (2), 122–132. https://doi.org/10.1215/07990537-8604538

62. Long, J.W. and F.K. Lake, 2018: Escaping social-ecological traps through tribal stewardship on national forest lands in the Pacific Northwest, United States of America. *Ecology and Society*, **23** (2). https://doi.org/10.5751/es-10041-230210

63. Rodríguez-Díaz, C.E., 2018: Maria in Puerto Rico: Natural disaster in a colonial archipelago. *American Journal of Public Health*, **108** (1), 30–32. https://doi.org/10.2105/ajph.2017.304198

64. Kurashima, N., L. Fortini, and T. Ticktin, 2019: The potential of Indigenous agricultural food production under climate change in Hawai'i. *Nature Sustainability*, **2** (3), 191–199. https://doi.org/10.1038/s41893-019-0226-1

65. Cha, J.M., 2020: Ch. 4. Just transition: Tools for protecting workers and their communities at risk of displacement due to climate policy. In: *Putting California on the High Road: A Jobs and Climate Action Plan for 2030*. University of California, Berkeley, 147–175. https://laborcenter.berkeley.edu/wp-content/uploads/2020/08/Chapter-4-Just-Transition-Putting-California-on-the-High-Road.pdf

66. Wright, A., 2021: Building Stronger Tribal Economies: A Four-Part Series. Blue Stone Insights. https://bluestonestrategy.com/building-stronger-tribal-economies-a-four-part-series/

67. Begay, S.K., 2018: How Citizen Potawatomi Nation utilizes energy efficiency and renewable energy to address its high energy burden. *The Electricity Journal*, **31** (6), 16–22. https://doi.org/10.1016/j.tej.2018.07.005

68. Cambou, D. and G. Poelzer, 2021: Ch. 10. Enhancing energy justice in the Arctic: An appraisal of the participation of Arctic indigenous peoples in the transition to renewable energy. In: *Renewable Economies in the Arctic*. Natcher, D.C. and T. Koivurova, Eds. Routledge, London, UK, 19. https://doi.org/10.4324/9781003172406

69. Necefer, L., G. Wong-Parodi, and M.J. Small, 2020: Governing energy in conflicted resource contexts: Culture, cost, and carbon in the decision-making criteria of the Navajo Nation. *Energy Research & Social Science*, **70**, 101714. https://doi.org/10.1016/j.erss.2020.101714

70. Sandoval, C.J.K., 2018: Energy access is energy justice: The Yurok Tribe's trailblazing work to close the Native American reservation electricity gap. In: *Energy Justice*. Salter, R., C.G. Gonzalez, M.H. Dworkin, R.A. Mastor, and E.K. Warner, Eds. Edward Elgar Publishing, 166–207. https://ssrn.com/abstract=3557121

71. Sandoval, C.J.K., 2020: Principles to Advance Energy Justice for Native Americans. EBA Brief. Energy Bar Association, 21 pp. https://doi.org/10.2139/ssrn.3770406

72. Strand, H., 2018: Breaking barriers to renewable energy production in the North American Arctic. *Alaska Law Review*, **35**, 67–115. https://scholarship.law.duke.edu/alr/vol35/iss1/4

73. Whitney, Z., 2020: Supporting Wind Development on Native American Tribal Lands. University of Hawai'i at Hilo, 149–153 pp. https://hilo.hawaii.edu/campuscenter/hohonu/volumes/documents/SupportingWindDevelopmentonNativeAmericanTribalLands.pdf

74. Wildcat, D., R. Blake, J.C. Collard, Lomayestewa, D. Marks-Marino, K. Morales, H. Mullen, A. Samoy, A. Walker, F. Wilkinson, and K. Whyte, 2021: Ch. 7. Energy & a just transition. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 190–209. http://nau.edu/stacc2021

75. Brewer II, J.P., S. Vandever, and J.T. Johnson, 2018: Towards energy sovereignty: Biomass as sustainability in interior Alaska. *Sustainability Science*, **13** (2), 417–429. https://doi.org/10.1007/s11625-017-0441-5

76. O'Rourke, E. and J. Zoellick, 2020: Energy Paths for the Yurok People. DOE-YUROK-000008. U.S. Department of Energy, Office of Indian Energy Policy and Programs. https://doi.org/10.2172/1599208

77. Schelly, C., D. Bessette, K. Brosemer, V. Gagnon, K.L. Arola, A. Fiss, J.M. Pearce, and K.E. Halvorsen, 2020: Energy policy for energy sovereignty: Can policy tools enhance energy sovereignty? *Solar Energy*, **205**, 109–112. https://doi.org/10.1016/j.solener.2020.05.056

78. Souba, F. and P.B. Mendelson, 2018: Chaninik Wind Group: Lessons learned beyond wind integration for remote Alaska. *The Electricity Journal*, **31** (6), 40–47. https://doi.org/10.1016/j.tej.2018.06.008

79. Donatuto, J., L. Campbell, and W. Trousdale, 2020: The "value" of values-driven data in identifying Indigenous health and climate change priorities. *Climatic Change*, **158** (2), 161–180. https://doi.org/10.1007/s10584-019-02596-2

80. Tribal Adaptation Menu Team, 2019: Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu. Great Lakes Indian Fish and Wildlife Commission, Odanah, WI, 54 pp. https://forestadaptation.org/tribal-climate-adaptation-menu

81. Hasbrouck, T.R., T.J. Brinkman, G. Stout, E. Trochim, and K. Kielland, 2020: Quantifying effects of environmental factors on moose harvest in Interior Alaska. *Wildlife Biology*, **2020** (2). https://doi.org/10.2981/wlb.00631

82. VanWinkle, T.N. and J. Friedman, 2019: Between drought and disparity: American Indian farmers, resource bureaucracy, and climate vulnerability in the Southern Plains. *Journal of Agriculture, Food Systems, and Community Development*, **9** (B), 53–68. https://doi.org/10.5304/jafscd.2019.09b.022

83. Zentner, E., M. Kecinski, A. Letourneau, and D. Davidson, 2019: Ignoring Indigenous peoples—Climate change, oil development, and Indigenous rights clash in the Arctic National Wildlife Refuge. *Climatic Change*, **155** (4), 533–544. https://doi.org/10.1007/s10584-019-02489-4

84. Martin, C., J. Doyle, J. LaFrance, M.J. Lefthand, S.L. Young, E. Three Irons, and M.J. Eggers, 2020: Change rippling through our waters and culture. *Journal of Contemporary Water Research & Education*, **169** (1), 61–78. https://doi.org/10.1111/j.1936-704x.2020.03332.x

85. Donatuto, J., L. Campbell, C. Cooley, M. Cruz, J. Doyle, M. Eggers, T. Farrow Ferman, S. Gaughen, P. Hardison, C. Jones, D. Marks-Marino, A. Pairis, W. Red Elk, D. Sambo Dorough, and C. Sanders, 2021: Ch. 5. Health & wellbeing. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 159–173. http://nau.edu/stacc2021

86. Adams, A., R. Byron, B. Maxwell, S. Higgins, M. Eggers, L. Byron, and C. Whitlock, 2021: Climate Change and Human Health in Montana: A Special Report of the Montana Climate Assessment. Montana State University, Institute on Ecosystems, Center for American Indian and Rural Health Equity, Bozeman, MT, 216 pp. https://doi.org/10.15788/c2h22021

87. Karuk Tribe, 2019: Karuk Climate Adaptation Plan. Karuk Tribe Department of Natural Resources. https://karuktribeclimatechangeprojects.files.wordpress.com/2019/08/final-karuk-climate-adaptation-plan_july2019.pdf

88. McKinley, C.E., J.M. Scarnato, J. Liddell, H. Knipp, and S. Billiot, 2019: Hurricanes and indigenous families: Understanding connections with discrimination, social support, and violence on PTSD. *Journal of Family Strengths*, **19** (1). https://digitalcommons.library.tmc.edu/jfs/vol19/iss1/10/

89. Middleton, J., A. Cunsolo, A. Jones-Bitton, C.J. Wright, and S.L. Harper, 2020: Indigenous mental health in a changing climate: A systematic scoping review of the global literature. *Environmental Research Letters*, **15** (5), 053001. https://doi.org/10.1088/1748-9326/ab68a9

90. Vecchio, E.A., M. Dickson, and Y. Zhang, 2022: Indigenous mental health and climate change: A systematic literature review. *The Journal of Climate Change and Health*, **6**, 100121. https://doi.org/10.1016/j.joclim.2022.100121

91. Csevár, S., 2021: Voices in the background: Environmental degradation and climate change as driving forces of violence against Indigenous women. *Global Studies Quarterly*, **1** (3), ksab018. https://doi.org/10.1093/isagsq/ksab018

92. Scheidel, A., D. Del Bene, J. Liu, G. Navas, S. Mingorría, F. Demaria, S. Avila, B. Roy, I. Ertör, L. Temper, and J. Martínez-Alier, 2020: Environmental conflicts and defenders: A global overview. *Global Environmental Change*, **63**, 102104. https://doi.org/10.1016/j.gloenvcha.2020.102104

93. Scheidel, A., Á. Fernández-Llamazares, A.H. Bara, D. Del Bene, D.M. David-Chavez, E. Fanari, I. Garba, K. Hanaček, J. Liu, J. Martínez-Alier, G. Navas, V. Reyes-García, B. Roy, L. Temper, M.A. Thiri, D. Tran, M. Walter, and K.P. Whyte, 2023: Global impacts of extractive and industrial development projects on Indigenous Peoples' lifeways, lands, and rights. *Science Advances*, **9** (23), 9557. https://doi.org/10.1126/sciadv.ade9557

94. Wiecks, J., C. Avery, A. Boetcher, C. Cooley, M. Cruz, P. Hardison, C. Jones, C. Kriebs, and D. Marks-Marino, 2021: Ch. 4.1. Air. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 81–97. http://nau.edu/stacc2021

95. Johnson, M.P., 2021: 'Thirsty sugar lands': Environmental impacts of dams and Empire in Puerto Rico since 1898. *Environment and History*, **27** (3), 337–365. https://doi.org/10.3197/096734019x15631846928701

96. Zavaleta-Cortijo, C., J.D. Ford, I. Arotoma-Rojas, S. Lwasa, G. Lancha-Rucoba, P.J. García, J.J. Miranda, D.B. Namanya, M. New, C.J. Wright, L. Berrang-Ford, C. Carcamo, V. Edge, and S.L. Harper, 2020: Climate change and COVID-19: Reinforcing Indigenous food systems. *The Lancet Planetary Health*, **4** (9), e381–e382. https://doi.org/10.1016/s2542-5196(20)30173-x

97. Leonard, K., 2021: Sustaining Tribal fisheries: U.S. economic relief policies during COVID-19. *Sustainability*, **13** (22), 12366. https://doi.org/10.3390/su132212366

98. John-Henderson, N.A., B.J. Oosterhoff, L.R. Johnson, M. Ellen Lafromboise, M. Malatare, and E. Salois, 2022: COVID-19 and food insecurity in the Blackfeet Tribal Community. *Food Security*, **14** (5), 1337–1346. https://doi.org/10.1007/s12571-022-01292-x

99. Leonard, K., 2020: Medicine lines and COVID-19: Indigenous geographies of imagined bordering. *Dialogues in Human Geography*, **10** (2), 164–168. https://doi.org/10.1177/2043820620934941

100. Lunsford, L., M. Arthur, and C. Porter, 2021: African and Native American foodways and resilience: From 1619 to COVID-19. *Journal of Agriculture, Food Systems, and Community Development*, **10** (4), 241–265. https://doi.org/10.5304/jafscd.2021.104.008

101. Larson, R., 2020: Water law and the response to COVID-19. *Water International*, **45** (7–8), 716–721. https://doi.org/10.1080/02508060.2020.1835422

102. ANTHC, 2019: Portable Alternative Sanitation System Connects In-Home Sanitation Systems Where It Was Impossible Before. Alaska Native Tribal Health Consortium. https://www.anthc.org/news/portable-alternative-sanitation-system-connects-in-home-sanitation-systems-where-it-was-impossible-before/

103. Mitchell, F.M., 2020: American Indian water insecurity in the era of COVID-19. *Journal of Indigenous Social Development*, **9** (3), 67–75. https://journalhosting.ucalgary.ca/index.php/jisd/article/view/71067/54411

104. OCCHE, 2022: Climate Change and Health Equity. U.S. Department of Health and Human Services, Office of Climate Change and Health Equity. https://www.hhs.gov/climate-change-health-equity-environmental-justice/climate-change-health-equity/index.html

105. Stoler, J., W.E. Jepson, and A. Wutich, 2020: Beyond handwashing: Water insecurity undermines COVID-19 response in developing areas. *Journal of Global Health*, **10** (1), 010355. https://doi.org/10.7189/jogh.10.010355

106. Tanana, H., J. Combs, and A. Hoss, 2021: Water is life: Law, systemic racism, and water security in Indian Country. *Health Security*, **19** (1), 78–82. https://doi.org/10.1089/hs.2021.0034

107. Leonard, K., N. Welch, and A.A. Joseph, 2020: COVID-19 in Indigenous communities: Five protective factors of "exercising" sovereignty. In: *Sport and the Pandemic: Perspectives on COVID-19's Impact on the Sport Industry*. Pedersen, P.M., B.J. Ruihley, and B. Li, Eds. Routledge, New York, 236–246. https://digitalcommons.linfield.edu/busnfac_pubs/4/

108. Pember, M.A., 2020: Ojibwe people carry on wild rice tradition amid COVID-19. *Indian Country Today*, September 30, 2020. https://www.indianz.com/news/2020/09/30/indian-country-today-ojibwe-people-carry-on-wild-rice-tradition-amid-covid-19/

109. Wheat, S., S. Gaughen, J. Skeet, L. Campbell, J. Donatuto, J. Schaeffer, and C. Sorensen, 2022: Climate change and COVID-19: Assessing the vulnerability and resilience of U.S. Indigenous communities to syndemic crises. *The Journal of Climate Change and Health*, **8**, 100148. https://doi.org/10.1016/j.joclim.2022.100148

110. Emerson, M.A. and T. Montoya, 2021: Confronting legacies of structural racism and settler colonialism to understand COVID-19 impacts on the Navajo Nation. *American Journal of Public Health*, **111** (8), 1465–1469. https://doi.org/10.2105/ajph.2021.306398

111. Bowling, T., 2020: Burial at sea: Maryland's historic cemeteries at risk. *Natural Resources & Environment*, **34** (3), 39–43. https://www.americanbar.org/groups/environment_energy_resources/publications/natural_resources_environment/2019-20/winter/burial-sea-marylands-historic-cemeteries-risk/

112. Ezcurra, P. and I.C. Rivera-Collazo, 2018: An assessment of the impacts of climate change on Puerto Rico's Cultural Heritage with a case study on sea-level rise. *Journal of Cultural Heritage*, **32**, 198–209. https://doi.org/10.1016/j.culher.2018.01.016

113. Hutton, N.S. and T.R. Allen, 2020: The role of traditional knowledge in coastal adaptation priorities: The Pamunkey Indian Reservation. *Water*, **12** (12), 3548. https://doi.org/10.3390/w12123548

114. Leonard, K., 2021: WAMPUM adaptation framework: Eastern coastal Tribal Nations and sea level rise impacts on water security. *Climate and Development*, **13** (9), 842–851. https://doi.org/10.1080/17565529.2020.1862739

115. Mockta, T.K., P.Z. Fulé, A. Sánchez Meador, T. Padilla, and Y.-S. Kim, 2018: Sustainability of culturally important teepee poles on Mescalero Apache Tribal Lands: Characteristics and climate change effects. *Forest Ecology and Management*, **430**, 250–258. https://doi.org/10.1016/j.foreco.2018.08.017

116. Benner, J., J. Nielsen, and K. Lertzman, 2021: Using traditional ecological knowledge to understand the diversity and abundance of culturally important trees. *Journal of Ethnobiology*, **41** (2), 209–228. https://doi.org/10.2993/0278-0771-41.2.209

117. Marks-Block, T., F.K. Lake, and L.M. Curran, 2019: Effects of understory fire management treatments on California hazelnut, an ecocultural resource of the Karuk and Yurok Indians in the Pacific Northwest. *Forest Ecology and Management*, **450**, 117517. https://doi.org/10.1016/j.foreco.2019.117517

118. Emery, M.R., 2019: Voices from Maple Nation: Indigenous women's climate summit. *New England Society of American Foresters News Quarterly*, **80** (4), 8–10. https://www.fs.usda.gov/research/treesearch/59171

119. Langston, N., 2021: *Climate Ghosts: Migratory Species in the Anthropocene*. Brandeis University Press, 201 pp. https://doi.org/10.2307/j.ctv2n7j1hf

120. Dorais, L.-J., 2020: *Words of the Inuit: A Semantic Stroll Through a Northern Culture*. University of Manitoba Press, 344 pp. https://uofmpress.ca/books/detail/words-of-the-inuit

121. Weyapuk, W. and I. Krupnik, 2012: Kinikmi Sigum Qanuq Ilitaavut, Wales Inupiaq Sea Ice Dictionary. Arctic Studies Center, Washington, DC. https://repository.si.edu/handle/10088/94115

122. Wilson, K.J., A. Arreak, J. Itulu, Sikumiut Community Management Committee, G.J. Ljubicic, and T. Bell, 2021: "When we're on the ice, all we have is our Inuit Qaujimajatuqangit": Mobilizing Inuit knowledge as a sea ice safety adaptation strategy in Mittimatalik, Nunavut. *Arctic*, **74** (4), 418–583. https://doi.org/10.14430/arctic74212

123. IPN, n.d.: Indigenous Phenology Network [Website], accessed May 25, 2023. https://www.usanpn.org/nn/indigenous-phenology-network

124. AIJ, 2020: Rights of Indigenous People in Addressing Climate-Forced Displacement: Complaint Submitted to the United Nations' Special Rapporteurs. Alaska Institute for Justice. https://climatecasechart.com/non-us-case/rights-of-indigenous-people-in-addressing-climate-forced-displacement/

125. Tanana, H., 2022: Protecting Tribal Public Health from Climate Change Impacts. University of Utah College of Law Research Paper No. 511. Northeastern Law Review, 43 pp. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4212778

126. GAO, 2022: Alaska Native Issues: Federal Agencies Could Enhance Support for Native Village Efforts to Address Environmental Threats. GAO-22-104241. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-22-104241.pdf

127. Schwebel, M.B., 2018: Climate change perceptions and preparation in the United States territories in the Pacific: American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands. *Island Studies Journal*, **13** (1), 135–148. https://doi.org/10.24043/isj.57

128. Serrano, S.K. and I.F. Tapu, 2022: Reparative justice in the U.S. territories: Reckoning with America's colonial climate crisis. *California Law Review*, **110**. https://californialawreview.org/print/reparative-justice-in-the-u-s-territories-reckoning-with-americas-colonial-climate-crisis/

129. Indianz.com, 2021: H.R.4352 – Legislative fix to U.S. Supreme Court decision in *Carcieri v. Salazar*. *Native American News*. Indianz.com. https://www.indianz.com/news/2021/12/01/h-r-4352-legislative-fix-to-u-s-supreme-court-decision-in-carcieri-v-salazar/

130. Keene, E., 2017: Lessons from relocations past: Climate change, tribes, and the need for pragmatism in community relocation planning. *American Indian Law Review*, **42** (1), 259–289. https://www.jstor.org/stable/26492279

131. NCAI, 2020: Protecting Tribal Lands and Environment and Addressing Climate Change. National Congress of American Indians. https://www.ncai.org/conferences-events/ncai-events/2020_tuid_homelands_and_climate_-final.pdf

132. USET, 2019: Testimony of United South and Eastern Tribes Sovereignty Protection Fund Submitted to the House Natural Resources Subcommittee for Indigenous People of the United States for the Record of the February 12, 2019 Hearing, "The Impacts of Climate Change on Tribal Communities". United South and Eastern Tribes, 4 pp. https://www.usetinc.org/wp-content/uploads/2019/02/USET-SPF-Testimony-to-HNR_Climate-Change-Tribal-Nations-FINAL-022619.pdf

133. NAIHC, 2017: Flood Mapping on Native American Reservations. National American Indian Housing Council, 2 pp. https://naihc.net/wp-content/uploads/2018/03/Flood-Mappin-White-Paper-FINAL.pdf

134. Fayazi, M., I.-A. Bisson, and E. Nicholas, 2020: Barriers to climate change adaptation in indigenous communities: A case study on the mohawk community of Kanesatake, Canada. *International Journal of Disaster Risk Reduction*, **49**, 101750. https://doi.org/10.1016/j.ijdrr.2020.101750

135. Tanana, H.J. and J.C. Ruple, 2021: Synching Science and Policy to Address Climate Change in Tribal Communities. Research Paper No. 467. University of Utah, SJ Quinney College of Law. https://doi.org/10.2139/ssrn.3919210

136. Trahant, M., 2018: Tribal people face disproportionate impact from climate change. *Indian Country Today*, November 27, 2018. https://www.indianz.com/news/2018/11/27/mark-trahant-climate-change-threatens-na.asp

137. National Drought Mitigation Center, 2023: U.S. Drought Monitor. University of Nebraska-Lincoln, National Drought Mitigation Center, accessed August 16, 2023. https://droughtmonitor.unl.edu/Maps/MapArchive.aspx

138. Cozzetto, K., D. Marks-Marino, and STACCWG, 2021: Executive summary. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 6–14. http://nau.edu/stacc2021

139. Domestic Policy Council, 2021: The White House Tribal Nations Summit Progress Report. The White House, Washington, DC, 38 pp. https://www.whitehouse.gov/wp-content/uploads/2021/11/wh-tribal-nations-summit-progress-report.pdf

140. GAO, 2022: Tribal and Native American Issues. U.S. Government Accountability Office. https://www.gao.gov/tribal-and-native-american-issues

141. U.S. Commission on Civil Rights, 2018: Broken Promises: Continuing Federal Funding Shortfall for Native Americans. Briefing Report. U.S. Commission on Civil Rights, Washington, DC. https://www.usccr.gov/files/pubs/2018/12-20-broken-promises.pdf

142. Whyte, K., J. Maldonado, S. McNeeley, H. Mullen, and R. Novak, 2021: Ch. 1. History of Indigenous peoples in national climate assessments. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 27–33. http://nau.edu/stacc2021

143. Treaty Indian Tribes in Western Washington, 2011: Treaty Rights At Risk: Ongoing Habitat Loss, the Decline of the Salmon Resource, and Recommendations for Change. Northwest Indian Fisheries Commission, Olympia, WA, 35 pp. https://salishsearestoration.org/wiki/File:NWIFC_2011_treaty_rights_at_risk.pdf

144. Whyte, K.P., 2013: Justice forward: Tribes, climate adaptation and responsibility. *Climatic Change*, **120** (3), 517–530. https://doi.org/10.1007/s10584-013-0743-2

145. CEQ, 2022: CEQ Summary of Tribal Consultations on America the Beautiful. White House Council on Environmental Quality, Washington, DC. https://www.whitehouse.gov/ceq/news-updates/2022/03/21/ceq-summary-of-tribal-consultations-on-america-the-beautiful/

146. Kennedy, S., 2022: This land is not our land, this land is their land: Returning national park lands to their rightful protectors. *American Indian Law Journal*, **10** (1), 3. https://digitalcommons.law.seattleu.edu/ailj/vol10/iss1/3/

147. Washburn, K.K., 2021: Facilitating Tribal Co-Management of Federal Public Lands. Wis. L. Rev. 263; Iowa Legal Studies Research Paper No. 2021-45. University of Iowa, College of Law. https://doi.org/10.2139/ssrn.3951290

148. Mills, M. and M. Nie, 2021: Bridges to a new era: A report on the past, present, and potential future of tribal co-managment on federal public lands. *Public Land & Resources Law Review*, **44**, 2. https://scholarworks.umt.edu/plrlr/vol44/iss1/2

149. Executive Office of the President, 2000: Executive Order 13175: Consultation and coordination with Indian tribal governments. *Federal Register*, **65** (218), 67249–67252. https://www.federalregister.gov/documents/2000/11/09/00-29003/consultation-and-coordination-with-indian-tribal-governments

150. Dockry, M.J., S.A. Gutterman, and M.A. Davenport, 2018: Building bridges: Perspectives on partnership and collaboration from the US Forest Service tribal relations program. *Journal of Forestry*, **116** (2), 123–132. https://doi.org/10.5849/jof-2016-106

151. David-Chavez, D.M., S. Valdez, J.B. Estevez, C. Meléndez Martínez, A.A. Garcia, K. Josephs, and A. Troncoso, 2020: Community-based (rooted) research for regeneration: Understanding benefits, barriers, and resources for Indigenous education and research. *AlterNative: An International Journal of Indigenous Peoples*, **16** (3), 220–232. https://doi.org/10.1177/1177180120952896

152. Emanuel, R.E. and D.E. Wilkins, 2020: Breaching barriers: The fight for Indigenous participation in water governance. *Water*, **12** (8). https://doi.org/10.3390/w12082113

153. Jacobson, M.A., R. Hajjar, E.J. Davis, and S. Hoagland, 2021: Learning from tribal leadership and the anchor forest concept for implementing cross-boundary forest management. *Journal of Forestry*, **119** (6), 605–617. https://doi.org/10.1093/jofore/fvab031

154. Sessions, J., J. Gordon, P. Rigdon, D. Motanic, and V. Corrao, 2017: Indian forests and forestry: Can they play a larger role in sustainable forest management? *Journal of Forestry*, **115** (5), 364–365. https://doi.org/10.5849/jof.2016-083r1

155. Braithwaite, J., 2022: This is no longer a Bristol Bay Fishery": Fisheries dispossession and colonial violence in Bristol Bay, Alaska. *Marine Policy*, **143**, 105172. https://doi.org/10.1016/j.marpol.2022.105172

156. Leonard, K., 2021: Turtle Island (North America) Indigenous higher education institutions and environmental sustainability education. *Journal of Comparative & International Higher Education*, **13**, 90–133. https://doi.org/10.32674/jcihe.v13isummer.3279

157. Blackwater, D., 2020: Broadband internet access: A solution to tribal economic development challenges. *The Indigenous Peoples' Journal of Law, Culture, & Resistance*, **6**, 93–116. https://www.jstor.org/stable/48671871

158. FCC Native Nations Communications Task Force, 2019: Improving and Increasing Broadband Deployment on Tribal Lands. Report to the Federal Communications Commission from the Tribal Members of the Task Force. Federal Communications Commission, 39 pp. https://www.fcc.gov/sites/default/files/nnctf_tribal_broadband_report.pdf

159. FEMA, 2019: Tribal Mitigation Planning Handbook. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/2020-06/fema-tribal-planning-handbook_05-2019.pdf

160. Rivera-Collazo, I.C., 2021: Climate change and archaeological sites: A case study for partnering cultural heritage and climate action. In: *Stemming the Tide: Global Strategies for Sustaining Cultural Heritage through Climate Change*. Rushfield, R., Ed. Smithsonian Institution Scholarly Press, Washington, DC, 25–38. https://doi.org/10.5479/si.14750727

161. David-Chavez, D., D.B. Ferguson, A. Curley, T. Lane, S. Yazzie, S. Leroy, and S. Russo Carroll, 2019: Policy Brief: Supporting Tribal Data Governance for Indigenous Community Climate Resilience. University of Arizona, Native Nations Institute and the Climate Assessment for the Southwest, Tucson, AZ. https://nni.arizona.edu/publications/policy-brief-supporting-tribal-data-governance-indigenous-community-climate-resilience

162. Walter, M., T. Kukutai, S.R. Carroll, and D. Rodriguez-Lonebear, Eds., 2020: *Indigenous Data Sovereignty and Policy*. 1st ed., Taylor & Francis, London, UK. https://doi.org/10.4324/9780429273957

163. Walter, M. and M. Suina, 2019: Indigenous data, Indigenous methodologies and Indigenous Data Sovereignty. *International Journal of Social Research Methodology*, **22** (3), 233–243. https://doi.org/10.1080/13645579.2018.1531228

164. Wheeler, H.C., F. Danielsen, M. Fidel, V. Hausner, T. Horstkotte, N. Johnson, O. Lee, N. Mukherjee, A. Amos, H. Ashthorn, Ø. Ballari, C. Behe, K. Breton-Honeyman, G.-B. Retter, V. Buschman, P. Jakobsen, F. Johnson, B. Lyberth, J.A. Parrott, M. Pogodaev, R. Sulyandziga, and N. Vronski, 2020: The need for transformative changes in the use of Indigenous Knowledge along with science for environmental decision-making in the Arctic. *People and Nature*, **2** (3), 544–556. https://doi.org/10.1002/pan3.10131

165. Carroll, S.R., I. Garba, O.L. Figueroa-Rodríguez, J. Holbrook, R. Lovett, S. Materechera, M. Parsons, K. Raseroka, D. Rodriguez-Lonebear, R. Rowe, R. Sara, J.D. Walker, J. Anderson, and M. Hudson, 2020: The CARE Principles for Indigenous Data Governance. *Data Science Journal*, **19** (1), 43. https://doi.org/10.5334/dsj-2020-043

166. Carroll, S.R., E. Herczog, M. Hudson, K. Russell, and S. Stall, 2021: Operationalizing the CARE and FAIR Principles for Indigenous Data Futures. *Scientific Data*, **8** (1), 108. https://doi.org/10.1038/s41597-021-00892-0

167. Galappaththi, E., 2022: Indigenous data sovereignty: Insights from climate change adaptation research. In: *American Fisheries Society Annual Meeting*. Spokane, WA, 21–25 August 2022. Presentation at the American Fisheries Society Annual Meeting.

168. Matson, L., G.H.C. Ng, M. Dockry, M. Nyblade, H.J. King, M. Bellcourt, J. Bloomquist, P. Bunting, E. Chapman, D. Dalbotten, M.A. Davenport, K. Diver, M. Duquain, W. Graveen, K. Hagsten, K. Hedin, S. Howard, T. Howes, J. Johnson, S. Kesner, E. Kojola, R. LaBine, D.J. Larkin, M. Montano, S. Moore, A. Myrbo, M. Northbird, M. Porter, R. Robinson, C.M. Santelli, R. Schmitter, R. Shimek, N. Schuldt, A. Smart, D. Strong, J. Torgeson, D. Vogt, and A. Waheed, 2021: Transforming research and relationships through collaborative tribal-university partnerships on manoomin (wild rice). *Environmental Science & Policy*, **115**, 108–115. https://doi.org/10.1016/j.envsci.2020.10.010

169. Carroll, S.R., Rodriguez-Lonebear, D., Martinez, A, 2019: Indigenous data governance: Strategies from United States Native nations. *Data Science Journal*, **18** (1), 31. https://doi.org/10.5334/dsj-2019-031

170. O'Brien, M., 2021: CARE principles for ESIP data repositories. In: *Earth Science Information Partners (ESIP)*. Edinburgh, UK, 22 April 2021. https://doi.org/10.5281/zenodo.5644249

171. Nursey-Bray, M., M. Parsons, and A. Gienger, 2022: *Urban nullius*? Urban Indigenous people and climate change. *Sustainability*, **14** (17). https://doi.org/10.3390/su141710830

172. Dent, L.A., J. Donatuto, L. Campbell, M. Boardman, J.J. Hess, and N.A. Errett, 2023: Incorporating Indigenous voices in regional climate change adaptation: Opportunities and challenges in the U.S. Pacific Northwest. *Climatic Change*, **176** (3), 27. https://doi.org/10.1007/s10584-023-03499-z

173. Evans, L.E., N. Dolšak, M.T. Plog, and A. Prakash, 2020: Native American tribal governments, cross-sectoral climate policy, and the role of intertribal networks. *Climatic Change*, **160** (1), 35–43. https://doi.org/10.1007/s10584-019-02641-0

174. Dittmer, K., 2013: Changing streamflow on Columbia basin tribal lands—Climate change and salmon. *Climatic Change*, **120** (3), 627–641. https://doi.org/10.1007/s10584-013-0745-0

175. Dockry, M.J., S.J. Hoagland, A.D. Leighton, J.R. Durglo, and A. Pradhananga, 2023: An assessment of American Indian forestry research, information needs, and priorities. *Journal of Forestry*, **121** (1), 49–63. https://doi.org/10.1093/jofore/fvac030

176. Gephart, L., 2009: Tribal salmon restoration and climate change in the Pacific Northwest. *Ecological Restoration*, **27** (3), 263. https://doi.org/10.3368/er.27.3.263

177. Singel, W., 2018: Indigenous responses to climate change and water quality concerns in the Great Lakes. *Sea Grant Law & Policy Journal*, **9**, 62. https://doi.org/10.17613/z4yr-yz15

178. Krosby, M., G. Bridge, E.T. Asinas, and S. Hall, 2023: Moving transboundary conservation from Indigenous engagement to Indigenous leadership: Working across borders for a resilient Cascadia. *Parks Stewardship Forum*, **39** (1). https://doi.org/10.5070/p539159903

179. Nursey-Bray, M., R. Palmer, A.M. Chischilly, P. Rist, and L. Yin, 2022: Ch. 4. Tribal capacity building and adaptation planning: The United States. In: *Old Ways for New Days: Indigenous Survival and Agency in Climate Changed Times*. Nursey-Bray, M., R. Palmer, A.M. Chischilly, P. Rist, and L. Yin, Eds. Springer, Cham, Switzerland, 57–76. https://doi.org/10.1007/978-3-030-97826-6_4

180. NDN Collective Climate Justice Team, 2021: Memo: How 'The Build Back Better Act' Can Meaningfully Mobilize Investment to Indigenous Communities & Uphold Free Prior and Informed Consent in the Process. NDN Collective, Rapid City, SD. https://ndncollective.org/memo-how-the-build-back-better-act-can-meaningfully-mobilize-investment-to-indigenous-communities-uphold-free-prior-and-informed-consent-in-the-process/

181. *Hearing: A Call to Action: Native Communities' Priorities in Focus for the 117th Congress, United States Senate, Committee on Indian Affairs*, 2021: United States Congress, One Hundred Seventeenth, First Session. https://www.govinfo.gov/content/pkg/CHRG-117shrg44248/html/CHRG-117shrg44248.htm

182. BIA, 2021: National Climate Assessment: Indigenous Peoples Resilience Actions. U.S. Bureau of Indian Affairs, Tribal Climate Resilience Program. https://biamaps.doi.gov/portal/apps/webappviewer/index.html?id=53794ae1ce054029bd5b55bcf269434c

183. Dockry, M.J., 2020: Indigenous rights and empowerment in natural resource management and decision making as a driver of change in U.S. forestry. In: *Drivers of Change in U.S. Forests and Forestry Over the Next 20 Years*. Dockry, M.J., D.N. Bengston, and L.M. Westphal, Eds. U.S. Department of Agriculture, Forest Service, Northern Research Station, Madison, WI, 76–83. https://doi.org/10.2737/nrs-gtr-p-197-paper8

184. Grossman, Z., 2008: Indigenous nations' responses to climate change. *American Indian Culture and Research Journal*, **32**, 5–27. https://doi.org/10.17953/aicr.32.3.n561082k204ul53g

185. Gwich'in Steering Committee, 2020: Arctic Indigenous Climate Change Summit Report. Gwich'in Nation. https://ourarcticrefuge.org/wp-content/uploads/2022/09/aics2019-report-final.pdf

186. ITEP, 2022: Tribal Profiles. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. https://www7.nau.edu/itep/main/tcc/tribes/

187. Lubchenco, J., K. Leonard, R. Hilborn, and K. Kryc, 2017: Full Committee Hearing: Ocean Climate Action: Solutions to the Climate Crisis. U.S. Natural Resources Committee. https://www.congress.gov/116/meeting/house/111092/witnesses/HMTG-116-II00-Wstate-LubchencoJ-20201117.pdf

188. Steen-Adams, M., D. Sampson, C. Jones, K. Lynn, and J. Mankowski, 2020: Tribal Review of the 2020 Congressional Action Plan on the Climate Crisis. Affiliated Tribes of Northwest Indians, Portland, OR, 80 pp. https://atnitribes.org/climatechange/wp-content/uploads/2020/11/ATNI_Tribal-review-of-CAP_11.7.20H.pdf

189. U.S. Federal Government, 2021: Tribal Resilience Resource Guide. U.S. Climate Resilience Toolkit. https://toolkit.climate.gov/tool/tribal-resilience-resource-guide

190. Latulippe, N. and N. Klenk, 2020: Making room and moving over: Knowledge co-production, Indigenous knowledge sovereignty and the politics of global environmental change decision-making. *Current Opinion in Environmental Sustainability*, **42**, 7–14. https://doi.org/10.1016/j.cosust.2019.10.010

191. UNESCO, 2020: Mobilizing Indigenous and Local Knowledge Solutions: Addressing Climate Impacts and Vulnerabilities. A Perspective from the Caribbean Region. United Nations Educational, Scientific, and Cultural Organization, Georgetown, Guyana. https://www4.unfccc.int/sites/submissionsstaging/documents/202009071542---unesco%20links%20sids_caribbean%20ilk-climate%20workshop%20report__final%20draft%5b3%5d.pdf

192. Lac du Flambeau Tribe, 2019: Hazard Mitigation Plan. Chapman, E., B. Gauthier, S. Petersen, G. Haddow, and D. Cappola, Eds. Federal Emergency Management Agency, 104 pp. http://www.ldftribe.com/resilience

193. Schramm, P.J., A.L.A. Janabi, L.W. Campbell, J.L. Donatuto, and S.C. Gaughen, 2020: How Indigenous communities are adapting to climate change: Insights from the Climate-Ready Tribes Initiative. *Health Affairs*, **39** (12), 2153–2159. https://doi.org/10.1377/hlthaff.2020.00997

194. Morales, K., 2021: Climate Change 202: Tribal Hazard Mitigation Planning Cohort. Northern Arizona University, Institute for Tribal Environmental Professionals, Climate Change Program. https://www7.nau.edu/itep/main/tcc/tribes/ntnl_thmp

195. BIA, 2023: Tribal Climate Resilience Annual Awards Program. U.S. Department of the Interior, Bureau of Indian Affairs, Washington, DC, accessed September 12, 2023. https://www.bia.gov/service/tcr-annual-awards-program

196. GLIFWC Climate Change Team, 2023: Aanji-Bimaadiziimagak O'ow Aki. Great Lakes Indian Fish and Wildlife Commission, Odanah, WI, 332 pp. https://glifwc.org/climatechange/

197. Brown, A., 2020: Tribes expect little help in fight to protect elders from coronavirus. *The Pew Charitable Trusts*, March 19, 2020. https://www.pewtrusts.org/en/research-and-analysis/blogs/stateline/2020/03/19/tribes-expect-little-help-in-fight-to-protect-elders-from-coronavirus

198. Avitt, A., 2021: Tribal and Indigenous Fire Tradition. U.S. Department of Agriculture, Forest Service, Fire and Aviation Management. https://www.fs.usda.gov/features/tribal-and-indigenous-heritage

199. Onondaga Nation, 2015: TSHA' THONSWATHA': The Journey to a New Firehouse. Onondaga Nation. https://www.onondaganation.org/news/2015/tsha-thonswatha-the-journey-to-a-new-firehouse/

200. Dockry, M.J., K. Hall, W. Van Lopik, and C.M. Caldwell, 2016: Sustainable development education, practice, and research: An indigenous model of sustainable development at the College of Menominee Nation, Keshena, WI, USA. *Sustainability Science*, **11** (1), 127–138. https://doi.org/10.1007/s11625-015-0304-x

201. Northwest Treaty Tribes, 2020: Swinomish Revives Ancient Clam Gardens to Fight Climate Change. Northwest Indian Fisheries Commission, Northwest Treaty Tribes. https://nwtreatytribes.org/swinomish-revives-ancient-clam-gardens-to-fight-climate-change/

202. Bowra, A., A. Mashford-Pringle, and B. Poland, 2021: Indigenous learning on Turtle Island: A review of the literature on land-based learning. *Canadian Geographies*, **65** (2), 132–140. https://doi.org/10.1111/cag.12659

203. Johnson-Jennings, M., S. Billiot, and K. Walters, 2020: Returning to our roots: Tribal health and wellness through land-based healing. *Genealogy*, **4** (3). https://doi.org/10.3390/genealogy4030091

204. Irlbacher-Fox, S. and R. MacNeill, 2020: Indigenous governance is an adaptive climate change strategy. *Northern Review*, **49**, 271–275. https://doi.org/10.22584/nr49.2020.019

205. The Red Nation, 2021: *The Red Deal: Indigenous Action to Save Our Earth*. Common Notions. https://www.commonnotions.org/the-red-deal

206. Donatuto, J., L. Campbell, J.K. LeCompte, D. Rohlman, and S. Tadlock, 2020: The story of 13 moons: Developing an environmental health and sustainability curriculum founded on Indigenous first foods and technologies. *Sustainability*, **12** (21), 8913. https://doi.org/10.3390/su12218913

207. Ullrich, J.S., 2019: For the love of our children: An Indigenous connectedness framework. *AlterNative: An International Journal of Indigenous Peoples*, **15** (2), 121–130. https://doi.org/10.1177/1177180119828114

208. Britten, M. and D. Deane-Ryan, 2020: Global Scan of Youth-Led Organisations Active on Climate and/or Biodiversity and Youth-Supporting Partners. Robert H. N. Ho Family Foundation. http://www.rhfamilyfoundation.org/p/RHFF_2020_Global_Scan_of_Youth_Led_Organisations_Exec_Sum_Full_Version.pdf

209. IIYC, 2023: International Indigenous Youth Council [Website], accessed May 23, 2023. https://indigenousyouth.org/

210. Privott, M., 2019: An ethos of responsibility and Indigenous women water protectors in the #NoDAPL movement. *American Indian Quarterly*, **43** (1), 74–100. https://doi.org/10.5250/amerindiquar.43.1.0074

211. NCAI, 2022: The Native Youth Leadership Summit: Conference Agenda. National Congress of American Indians, accessed September 29, 2022. https://www.ncai.org/events/2022/02/14/the-native-youth-leadership-summit-nyls-2022

212. UNITY, 2021: A Platform to Help Out Our Environment, Our Community, and the World. United National Indian Tribal Youth. https://unityinc.org/native-youth/a-platform-to-help-out-our-environment-our-community-and-the-world/

213. Fillmore, H.M., L. Singletary, and J. Phillips, 2018: Assessing tribal college priorities for enhancing climate adaptation on reservation lands. *Journal of Contemporary Water Research & Education*, **163** (1), 64–78. https://doi.org/10.1111/j.1936-704x.2018.03270.x

214. Kuslikis, A., 2020: Native knowledge for New Horizons: AIHEC's STEM initiatives. *Tribal College: Journal of American Indian Higher Education*, **31** (3), 18–21. https://tribalcollegejournal.org/native-knowledge-for-new-horizons-aihecs-stem-initiatives/

215. Paskus, L., 2015: Climate change working group meets at SIPI. *Tribal College: Journal of American Indian Higher Education*, **26** (4), 15–16. https://tribalcollegejournal.org/climate-change-working-group-meets-at-sipi/

216. Lubeck, A., W. LaPointe, L. LaPointe, and N. MartinRogers, 2021: Theory of Change: Mni Ki Wakan Decade of Water Summit. Wilder Research, Saint Paul, MN. https://www.wilder.org/sites/default/files/imports/MniKiWakan_DecadeOfWaterSummit_10-21.pdf

217. Warden, A.A., 2011: Calling All Polar Bears: A One-Woman Show. Allison Akootchook Warden, Minneapolis, MN. https://www.allisonwarden.com/calling-all-polar-bears.html

218. Pala Environmental Department, 2022: Tribes, Health, and Climate Change Short-Video Series. Tribal Climate Health. https://tribalclimatehealth.org/video-series/

219. Palmer, A. and C. Boutsikaris, 2021: Inhabitants: An Indigenous Perspective. Inhabitants Films. https://www.inhabitantsfilm.com/

220. Brewer, S. and M. Trahant, 2021: *Decolonizing Journalism Media By, For and About Indigenous Peoples. Moderators: Amy Stretten and Robert Pluma [Video]*. Craig Newmark Graduate School of Journalism. https://www.youtube.com/watch?v=rMyG-LgV7Ow

221. U.S. House Select Committee on the Climate Crisis, 2020: Solving the Climate Crisis: The Congressional Action Plan for a Clean Energy Economy and a Healthy, Resilient, and Just America. U.S. House Select Committee on the Climate Crisis, 538 pp. https://www.preventionweb.net/publication/solving-climate-crisis-congressional-action-plan-clean-energy-economy-and-healthy

222. Goldtooth, D., A. Saldamando, K. Gracey, T. Goldtooth, and C. Rees, 2021: Indigenous Resistance Against Carbon. Rees, C., Ed. Oil Change International, Washington, DC. https://www.ienearth.org/indigenous-resistance-against-carbon/

223. Belfer, E., J.D. Ford, M. Maillet, M. Araos, and M. Flynn, 2019: Pursuing an indigenous platform: Exploring opportunities and constraints for indigenous participation in the UNFCCC. *Global Environmental Politics*, **19** (1), 12–33. https://doi.org/10.1162/glep_a_00489

224. USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/nca4.2018

Fifth National Climate Assessment: Chapter 17

# Climate Effects on US International Interests

# Chapter 17. Climate Effects on US International Interests

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# Introduction

Globally, climate change is rapid and widespread and will continue through midcentury even if emissions are cut sharply, intensifying events such as extreme heatwaves, heavy rainfall, and drought.[1] The acute and accelerating impacts outside of US borders on food systems, health, human well-being, built and natural systems, and economic sectors[2] affect US national interests and compound the impacts of warming within the United States. The pace of emissions reduction and adaptation response would need to accelerate this decade both to limit warming to 1.5°C (2.7° F) or 2°C (3.6° F) above preindustrial levels and to build resilience to existing and future climate impacts (KMs 2.3, 32.1).[2,3]

In a globally connected world, climate impacts can affect multiple sectors at once and have cascading effects that cut across sectors and geographies (KM 17.1). The direct impacts of climate change globally on people, ecosystems, and infrastructure, as well as the global transition to cleaner, lower-emissions technologies and economies, affect critical US interests including national security (KM 17.2); economics, trade, and investment (KM 17.3); and sustainable development (KM 17.4).

Despite documented evidence of increasing climate change risks, mitigation and adaptation responses by public and private sectors are not yet sufficient to avoid rising losses of life, biodiversity, infrastructure, and economic opportunity.[1,2] Proactive early adaptation and mitigation action can reduce losses from climate change and extreme events, avoid locking in high emissions, and produce economic, social, and environmental benefits.[4] In particular, inclusive approaches can help reduce risks, improve effectiveness of responses, and create opportunities for Indigenous Peoples, local communities, and other marginalized and underrepresented populations (such as women, youth, older adults, and ethnic minorities) who are especially vulnerable to climate impacts and energy transitions (KM 31.2). Adapting to a changing climate depends in part on the effective integration of climate information into decision-making at global, regional, national, and local levels (Box 17.1; KM 31.4).

## Box 17.1. Climate Services at the International Level

Risk governance in the 21st century requires coherent actions across disaster risk reduction and climate change adaptation.[5,6] Systematic, coordinated approaches to climate information services (hereafter "climate services") can enable the development, quality-assurance, accessibility, stakeholder engagement, and knowledge-tailoring needed to support decision-making, from disaster risk reduction to resilient infrastructure development.[7,8,9] Climate services involves organizing different types of climate information (e.g., extreme-event return periods, slow onset trends such as sea level rise, in situ risk mapping, satellite-based data) across multiple timescales (e.g., weeks, seasons, decades, and longer), as well as technical assistance to help decision-makers interpret and integrate such information and related uncertainties into their planning and design processes. Such services support the coordination and implementation of international instruments and frameworks in which the United States has strong interests, including the Paris Agreement on climate change, the Sendai Framework for Disaster Risk Reduction 2015–2030, and the United Nations Sustainable Development Goals. Climate services are a central pillar of both the US President's Emergency Plan for Adaptation and Resilience (PREPARE), and the United Nations Secretary-General's initiative on Early Warnings for ALL (EW4ALL), launched in 2022. The EW4ALL goal is to ensure global coverage of action-oriented information systems to anticipate and reduce weather- and climate-related disasters by 2027.

There has been notable recent progress in data availability, including satellite-based information, climate- and disaster risk–related analytics, and networks for engaging communities across sectors such as national security, humanitarian interventions, water resources, human health, energy, food security, and infrastructure planning.[2,10,11,12] Examples include the Global Framework for Climate Services (GFCS), the European Union Copernicus Climate Change Service, Enhancing National Climate Services, and the Famine Early Warning Systems Network. The GFCS was initiated in 2009 and formally endorsed by the 187 member countries of the World Meteorological Organization, including the US.[8] However, many regions and countries lack sufficient capacity to assess climate impacts and cascading risks and to develop and deliver climate services to inform their immediate risk management and longer-term resilience goals.[13,14,15,16,17] While fundamentally important, observing networks are often inadequate in many regions. Many countries also lack comprehensive data on the local-level impacts of climate extremes and changes, hampering effective co-development and sustained delivery of services (KMs 31.3, 31.4; Ch. 23).[18] These gaps can undermine confidence in national and international climate service providers, sending users in search of alternative, competing, and less authoritative services, and, critically, can increase marginalization and inequity.

## Key Message 17.1

## Interdependent, Systemic Climate-Related Risks Increasingly Affect US Interests

In a globally connected world, climate change impacts on US interests are multifaceted, interconnected, and frequently exacerbated by social unrest and environmental degradation (*likely*, *high confidence*). The scale and speed of climate-related impacts to US interests are expected to increase, due in part to underlying interdependencies and to the projected intensification of climate change (*likely*, *high confidence*). Emerging systems- and scenarios-based approaches to integrative planning are being applied to account for interdependencies and competing priorities (*likely*, *high confidence*).

Climate-related risks manifest across multiple systems, sectors, geographic domains, and timescales.[19,20] Climate shocks in one or several parts of the built or natural system can lead to ripple effects around the world.[21,22] Climate change impacts—alone or in combination with compounding stressors—can cascade across interdependent systems, magnifying risks not typically attributed to climate change. The effects of these impacts can spill across geographies and markets and, in turn, affect multiple US security, economic, and sustainable development interests (Figure 17.1; Focus on Compound Events). Moreover, traditional approaches to managing risk are inadequate given the compound and cascading nature of system risk,

increasing the importance of accounting for system interdependency and uncertainty to reduce risk to US national interests.[23,24]

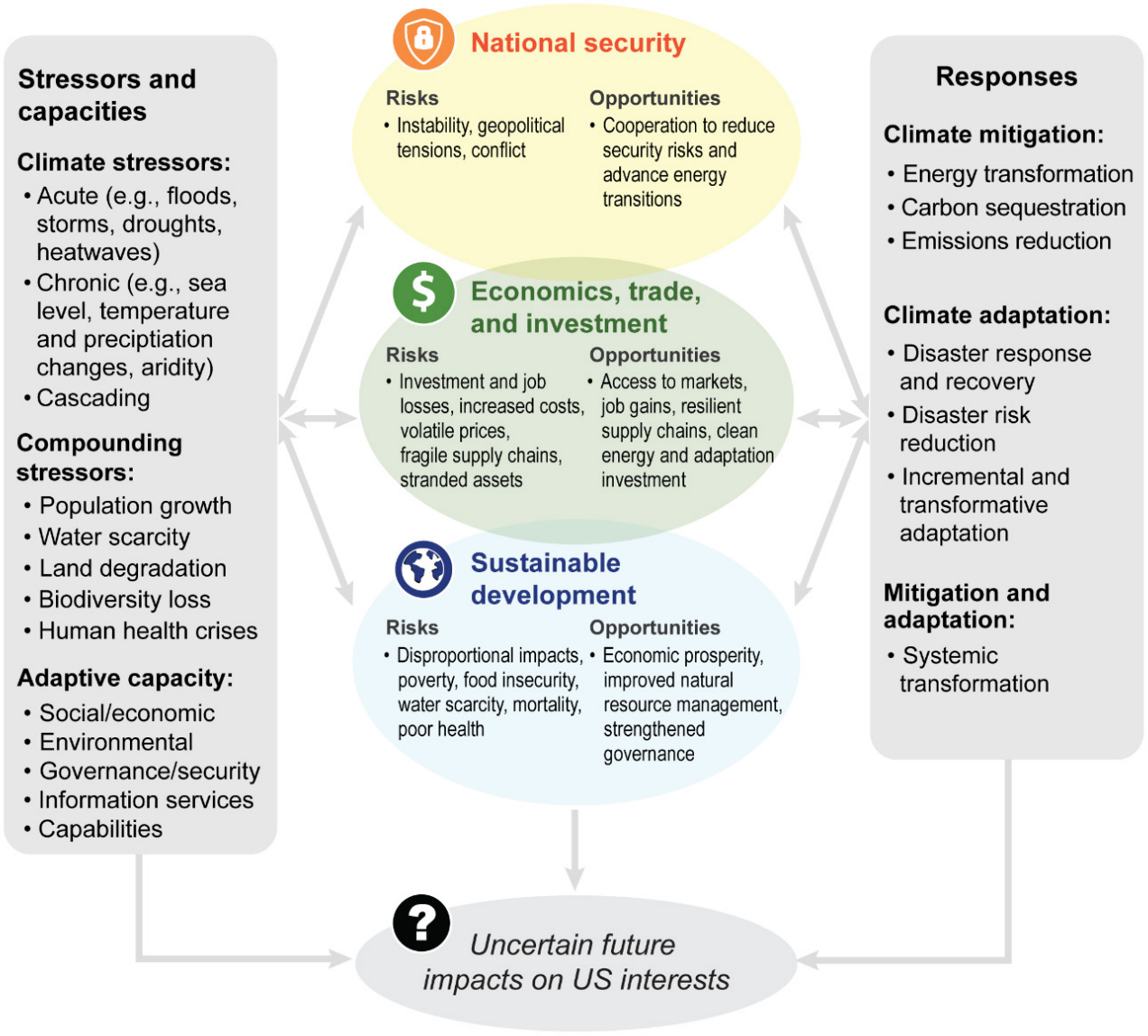
Climate change impacts affect the US's security, economy, and sustainable development interests by reducing local and global stability, disrupting livelihoods and economic growth, increasing poverty and global inequality[25,26] and compounding existing risks across US interests. For example, the Central American countries El Salvador, Guatemala, and Honduras are highly dependent on climate-sensitive agriculture, and climate change impacts disrupt rural livelihoods, health, and food security.[27] Drought and extreme storms have impacted millions of Central Americans by exacerbating conflict and insecurity, requiring significant humanitarian resources and fueling unprecedented migration, including to the United States.[28,29,30,31] Drought and extreme storms in Central America are expected to increase in frequency and severity due to climate change, threatening to further exacerbate these challenges.[32]

The combination of systemic global interdependencies and intensification of climate change is expected to increase both the scale and speed of climate change impacts.[1,33] Climate change—including increasing temperatures, changing rainfall patterns, and increased frequency of some extreme events—combines with stressors such as conflict, land degradation, biodiversity loss, population growth, and worsening human health to exacerbate food insecurity and potential famine.[34] For example, climate extremes have increased the incidence of multiple concurrent or consecutive breadbasket failures (e.g., poor harvests in major food-producing regions), threatening global food security and leading to cascading effects (e.g., social unrest and higher prices) across multiple geographies that affect US interests.[21,35,36] Since 2018, multiple stressors, including droughts in North America and the Horn of Africa, poor harvests in China and France, the COVID-19 pandemic, and the war in Ukraine have combined to severely test global food security, increasing fertilizer costs and food prices and decreasing food availability.[37]

Given the right conditions, however, interconnectedness can help mitigate risk. For example, food imports can address localized food insecurity and may become more prevalent given climate change impacts.[20,38] Transformative changes in human behavior that lead to "positive tipping points"—including the adoption of new technologies (e.g., energy transition to lower-emissions technologies) or approaches (e.g., regenerative agriculture approaches that increase climate resilience and sustainability of farm and food systems)—can help prevent the worst-case impacts of climate change.[39]

Traditional risk assessment and management approaches tend to focus on single sectors or locations rather than systems and the related complex interdependence of risks.[16,40] However, approaches to decision-making that address adaptation and mitigation early in the process at a systems level, considering the fullest suite of risks, interactions, and optimal response options, are advancing (Ch. 18).[41] Integrating responses vertically (across global, regional, and local levels) and/or horizontally (e.g., multistakeholder partnerships to codesign landscape-scale responses) offers promising insights for addressing these interdependencies across multiple scales and sectors.[42,43,44,45] Scenario planning, "nexus" approaches that address multiple sectors, and other co-development and participatory approaches are being applied to plan in the face of uncertainty, address linkages, and consider the role of response options themselves as risk drivers (Chs. 18, 31).[20,40] More experience is needed in applying and evaluating these emerging approaches to improve policy coherence and coordination across sectors and to better understand sensitivity to system changes and uncertainty.[40,46]

## Interconnected Interests and Cascading Impacts




**Future impacts to US interests are uncertain given complex system interdependencies and interactions between stressors, capacities, and responses.**

**Figure 17.1.** This figure illustrates how system interdependencies and the interconnected nature of climate change stressors and response choices can lead to uncertain future impacts on US interests (e.g., national security; economics, trade, and investment; and sustainable development). Climate and compounding stressors interact and present different degrees of potential impact to US interests given varying levels of adaptive capacity, sensitivity of interest areas, and the effectiveness of responses in addressing systemic risks and taking advantage of opportunities. The complexity of interacting stressors and interdependent systems can lead to cascading impacts, unintended consequences, and increased uncertainty on future impacts to US Interests. Adapted from Ringsmuth et al. 2022[47] [CC BY 4.0].

## Key Message 17.2

## Climate Change Exacerbates Risks to National Security

Climate change can contribute to political and social instability and, in some instances, to conflict (*likely*, *high confidence*). It impacts the operations and missions of defense, diplomacy, and development agencies critical to US national security (*very likely*, *high confidence*). The US Government, bilaterally and in collaboration with international partners, is increasingly addressing these implications through a range of diplomatic, development, and defense responses (*very likely*, *high confidence*).

Climate change exacerbates existing security challenges and risks, affecting a wide range of US national security interests.[48,49,50] Climate change impacts and responses can contribute to political and social instability as well as various forms of conflict.[2,49,51,52,53] Security-related concerns can also stem from the impacts of climate change on human lives and livelihoods, food and water security, biodiversity, and ecological and human health, as well as the responses to these impacts.[54,55,56] Inversely, conflict can exacerbate climate-related vulnerabilities, particularly affecting women, children, and overburdened populations.[57] This interplay between climate and conflict can hinder both mitigation and adaptation progress. The risk of destabilization and conflict connected to climate change has implications for US security interests distributed worldwide.

As shown in Table 17.1, the climate risks to US security interests span from local instability to geopolitical tension. In addition to the risks of instability and conflict, compounding dynamics include declining agricultural production and food security;[2] recruitment and influence for extremist or violent groups;[58] and declines in state capacity or legitimacy, including potential corruption, where governments cannot effectively respond to extreme weather events or long-term, chronic climate-connected impacts.[59,60,61]

**Table 17.1. Climate Risk Assessment to US Interests**

"Risks to US national security interests through 2040 will increase as countries respond to the intensifying physical effects of climate change."[50] For a full explanation, see the National Intelligence Estimate on "Climate Change and International Responses Increasing Challenges to US National Security Through 2040,"[50] from which this table is adapted.

| Risk | | 2021 | 2030 | 2040 |
|---|---|---|---|---|
| Climate Effects Impacting Country-Level Instability | Strain on energy and food systems | Low | Medium | High |
| | Negative health consequences | Low | Medium | Medium |
| | Internal insecurity and conflict | Low | Low | Medium |
| | Greater demand for aid and humanitarian relief | Medium | High | High |
| | Strain on military readiness | None | Low | Medium |
| Climate-Exacerbated Geopolitical Flashpoints | Miscalculation over strategic competition in the Arctic leading to conflict | None | Low | Medium |
| | Cross-border water tension and conflict | Low | Medium | High |
| | Cross-border migration attributed to climate impacts | Medium | High | High |
| | Ungoverned unilateral geoengineering | None | Low | Medium |
| Geopolitical Tensions over Climate Responses | Perception of insufficient contributions to reduce emissions | Low | Medium | High |
| | Carbon dioxide removal not at scale for countries' net-zero pledges | None | Low | Medium |
| | Developing countries' demands for financing and technology assistance | Medium | High | High |
| | Petro states resisting clean energy transition away from fossil fuels | Low | Medium | High |
| | Competition with China over key minerals and clean energy technologies | Low | Medium | High |
| | Contention over use of economic tools to advance climate interests | None | Low | Medium |

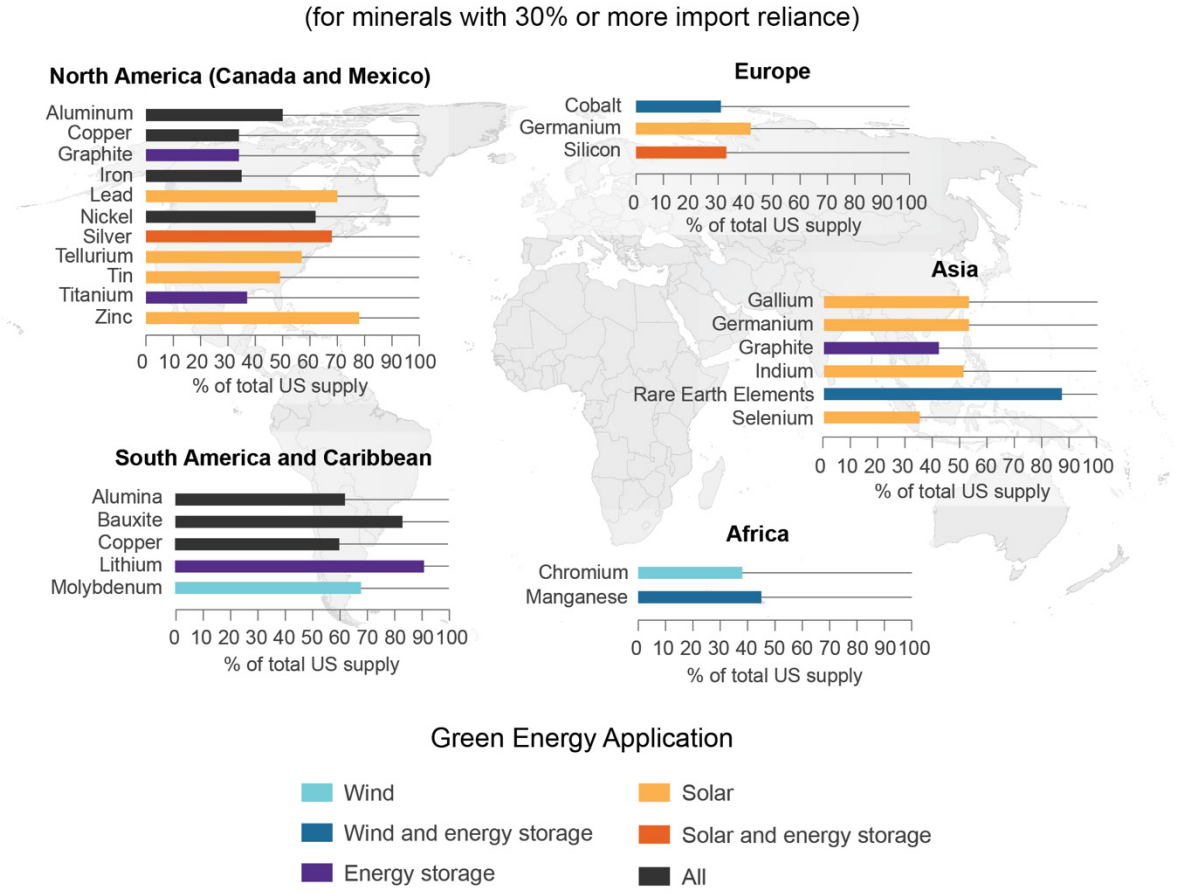
Mobility, both planned and forced, is a common adaptation response to a changing environment, contributing to displacement and migration that primarily occurs within countries and, at times, crosses national boundaries.[31,62,63] Climate change–related mobility, impacting both sending and receiving populations, is expected to increase.[50] Ongoing international engagement continues around climate change and mobility, but limited international governance that provides binding protections for people crossing national borders due to climate change results in varied state and regional responses.[64]

As countries continue to work toward adaptation and mitigation goals, alternative climate interventions are being considered to reduce the warming effect of greenhouse gases and avoid tipping points. One category

of alternative intervention is carbon dioxide removal, technical interventions to remove carbon dioxide from the atmosphere that can have impacts on food systems, biodiversity, and other systems (Chapter 32). Solar radiation modification (SRM) constitutes a variety of approaches to reduce sunlight reaching the lower atmosphere. The potential risks and benefits involving the use of SRM need to be considered relative to the risks and benefits associated with plausible trajectories of ongoing climate change not involving SRM.[65] SRM represents an area of growing interest for national security given the potential for unilateral action from state and non-state actors, evolving understanding of climate and societal impacts, and limited formal or informal mechanisms of engagement.[66,67] Understanding the risks and trade-offs of these alternative climate interventions is a rapidly growing field of study.

Climate change impacts are of particular concern in areas with limited resilience, unequal resource distribution, and/or weak governance structures. Unintended consequences of climate responses can also have important national security implications. For example, mitigation and adaptation efforts can unintentionally exacerbate new or existing conflicts and inequalities affecting marginalized populations.[68,69] Dynamics accompanying an energy transition such as price variability, loss of employment in the fossil fuel sector, and stranded assets for petroleum-producing countries may also contribute to internal protest and reduced support for strengthening international climate change mitigation efforts.[70] International climate change responses are shifting geostrategic and regional interests and priorities. These dynamics include competition for minerals and metals critical for mitigation and renewable energy.[71,72] Figure 17.2 displays the source of these materials, many of which are sourced outside the United States; however, note that China controls much of the market for mining and processing of many of these minerals and metals, leading to heavy dependence on China for resources critical for energy technologies. Moreover, the extraction and processing of these necessary inputs can heighten local ecological, political, and justice tensions.[73] Interests across the Arctic have also come under greater scrutiny as rapid warming opens up natural resource extraction possibilities, new sea transport routes, emergency response expectations in the event of accidents, and increased military activity, particularly by Russia (Chapter 29).

## US Net Import Reliance by Region for Minerals Necessary for Renewable Energy Technology




**US renewable energy technologies rely on imports of critical minerals from around the world.**

**Figure 17.2.** Many mineral inputs critical for renewable energy technologies are imported to the United States. This figure illustrates the diversity of location, mineral type, application, and scale of import reliance.[74] Adapted from Humphries 2019.[75]

Countries may also leverage climate change mitigation and adaptation policies to gain influence and foster new coalitions. Each country will experience a wide variety of climate-related security concerns that can generate new interests or alter existing interests within bilateral relationships.[50,61] For example, climate change impacts can disrupt global supply chains, such as those for food, energy, and critical minerals.[72] These disruptions affect US national security interests, particularly when occurring in tandem with responses to health, economic, and political crises such as those presented by COVID-19 and the war in Ukraine.

US national security, diplomatic, and development agencies are responding to the national security impacts of climate change and competing with other countries in these engagements.[76,77,78,79] Climate change impacts and responses have implications for defense, diplomacy, and development portfolios, including the climate-altered operational environment, US military and civilian infrastructure in partner countries, and humanitarian response.[49,79,80] Government responses include developing climate mitigation and adaptation plans; adapting operations, assessments, and infrastructure to be more resilient; building adaptive capacity and resilience to reduce future risk; and addressing threats and opportunities with a range of defense, diplomacy, and development approaches.[81,82,83] Within this geopolitical context, countries cooperate and compete and may try to take advantage of climate change impacts to gain influence.[49]

A number of multilateral forums (such as the UN Security Council, UN General Assembly, UN Environment Programme, European Union, North Atlantic Treaty Organization, African Union, and Organization for Security and Co-operation in Europe) recognize the interdependent nature of climate change impacts and their implications for national and regional security and have initiated collaborative responses to address transboundary risks.

Defense, diplomatic, and development institutions face increasing operations and emergency response expectations, often arising in new regions that are geopolitically relevant for US interests, as well as increasing requests for humanitarian support worldwide.[76,84] To ensure continuity of operations around the world, adaptation measures ensuring reliable and functional host country infrastructure and services at risk from climate change are a priority for US federal agencies. With international partners, the US Government is increasingly addressing climate-related risks to US national security through a wide range of responses. Assessing and responding to climate-related national security risks relies on the exchange of quality-assured information across global, regional, national, and local scales (see Box 17.1).

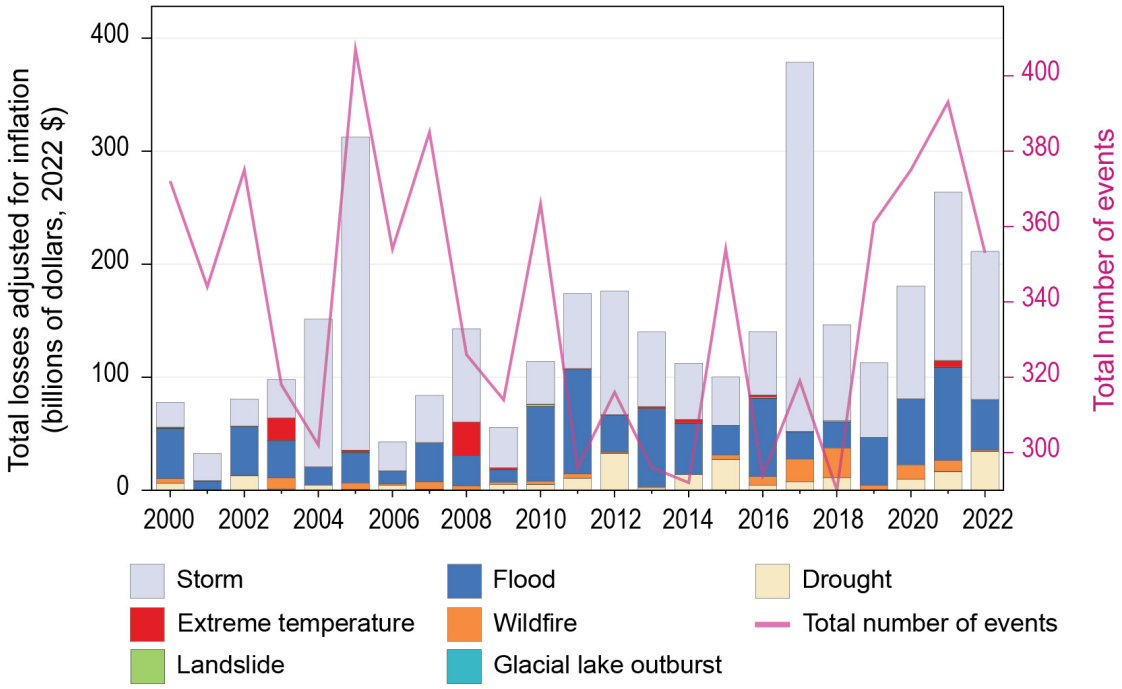
## Key Message 17.3

## Climate Change Presents Risks and Opportunities for US Economics, Trade, and Investments

The physical impacts of climate change are increasingly affecting global and regional economic growth (*very likely*, *high confidence*). These impacts have important implications for US economic, trade, and investment interests *(likely*, *medium confidence*). Global mitigation and adaptation responses by governments and businesses will likewise impact US economic interests, presenting both risks and potential opportunities for the US economy (*likely*, *medium confidence*). Public- and private-sector institutional, regulatory, financial, and market-based frameworks for climate mitigation and adaptation will influence these risks and opportunities (*likely*, *medium confidence*).

The impacts of climate change on global ecosystems, agriculture, human settlements, infrastructure, health, and migration translate into economic impacts that vary across regions and countries, as well as the extent to which effective adaptation measures are undertaken (Ch. 19).[2,85,86] Losses from climate-influenced disasters are globally widespread and growing, including from a wider range of climate-related events, such as wildfires and floods (Figure 17.3).[87,88,89] Although climate change has played a significant role in these trends, consensus is lacking on the extent to which increased losses are attributable to climate change versus other factors.[90,91]

## Climate-Related Disasters and Economic Losses




**This figure shows global trends in the number, growing costs, and increasing diversity of types of climate-related natural disasters since 2000.**

**Figure 17.3.** The total global losses associated with climate-related disasters have risen over the last two decades, with growing diversity in the types of climate-related events that lead to disasters (e.g., drought, wildfires, floods) and some annual spikes in storm-related losses. There is little correlation between losses and total number of disasters (suggesting increased losses may derive from increasing severity of disasters, increased value of assets, reporting discrepancies, or a combination of these). Figure credit: DOI, Winrock International, NOAA NCEI, and CISESS NC.

In addition to acute impacts, slow-onset climate impacts such as biodiversity loss and the effects of rising temperatures on health and agriculture in vulnerable regions, as well as nonlinear climate risks (tipping points), will affect economic growth.[92,93] A growing body of literature identifies sea level rise (SLR) as a key driver of economic impacts from climate change, with one study estimating global economy-wide GDP losses as high as 4% by 2100 from SLR-related coastal flooding if no adaptation measures are undertaken.[94]

Climate change impacts beyond US borders expose US economic, trade, and investment interests to risk because these interests are highly integrated in the global economy (Focus on Risks to Supply Chains; Ch. 19). For example, US foreign direct investment overseas and the value of exports and imports reached record levels in 2022.[95,96,97]

Although research relating climate change impacts outside of the US to direct impacts on US trade and investment interests is sparse, analyses suggest several risks to which US overseas investments and trade will be exposed, such as reduced asset values, greater risks of loan default, disincentives for new investments, and trade implications. For example, vulnerable countries face prolonged economic disruption from climate-related disasters, including loss of income and consumption and a higher risk of sovereign debt default.[98,99] Economic shocks in foreign countries are expected to reduce US agricultural exports, production, and farm income (Ch. 11).[100] According to one study, global temperature increases of 3.6°–5.76°F

(2.0°–3.2°C) would reduce midcentury GDP in the US, Canada, and the United Kingdom by 6%–9%, compared to growth without climate change.[101]

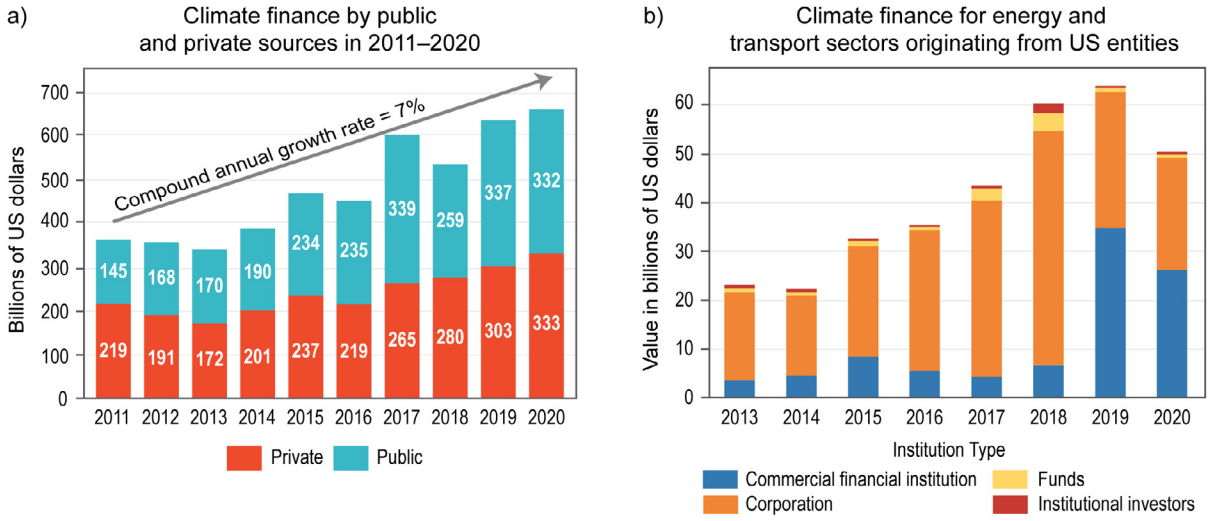
Global climate responses, including policy choices and market responses, present both risks and opportunities for US economic interests as other countries transition toward low-emissions, climate-resilient economies.[86,102] Transition risks include potential job losses, stranded assets, energy price increases, and potential negative impacts on the global financial system.[103] Adaptation responses that restrict development in risk-prone areas could limit options for US investors or leave existing assets exposed.[104]

The global transition, including increased global financing for mitigation and adaptation (Figure 17.4), will also generate innovation, trade, and investment opportunities for US firms (Ch. 19).[105,106,107] Opportunities for innovation and investment include low-carbon energy and carbon capture; transport and infrastructure; adaptation technologies in water, agriculture, health, and other sectors; resilient supply chains; and climate services.[108]

Governments and financial institutions are increasingly using blended finance, green bonds (fixed-income debt instruments that enable investments in climate change mitigation and adaptation), guarantees, and grants to unlock private-sector climate-related investment, including in areas such as land use, reforestation, and adaptation.[109,110] Multistakeholder partnerships are also harnessing market forces to reduce emissions, such as by encouraging deforestation-free commodity supply chains.[111] Workforce development and youth engagement programs are being implemented to prepare economies for the transition to climate-resilient development.[112,113]

Evolving regulatory and market frameworks and financing are important enabling conditions that will influence the effectiveness of global climate responses—including in achieving Paris Agreement climate mitigation and adaptation goals—and their impact on US economic interests.[108,114,115,116] Total global financing for climate mitigation and adaptation (Figure 17.4a) grew steadily from 2011–2020 but slowed in the years just prior to the pandemic and falls short of estimated needs to meet Paris Agreement goals and avoid the worst impacts of climate change.[117] Private-sector contributions increased between 2011 and 2020, although more slowly than public-sector contributions. Adaptation finance grew nearly three times faster than mitigation; however, methodologies for tracking adaptation finance are less developed than mitigation finance and subject to data gaps, particularly from the private sector.[118] While important caveats apply (see Figure 17.4 metadata), US investments in the energy and transport sectors have grown steadily between 2013 and 2020, largely tracking overall global climate finance increases, including in these sectors, albeit more concentrated on domestic US rather than overseas investments (Figure 17.4b).[118]

## Climate Finance




**Public and private contributions to global climate finance are increasing but not at the pace necessary to avoid the worst impacts of climate change.**

**Figure 17.4.** (**a**) The public and private sectors provided $4.8 trillion in climate finance in total between 2011 and 2020, with the private sector responsible for about half. (**b**) Data on private finance flows originating from the US are most comprehensive for the energy and transport sectors. Figure credits: (a) adapted from Naran et al. 2022[118] [CC BY-NC-SA 4.0]; (b) DOI, Winrock International, and Climate Policy Initiative.

Regulations and economic incentives supporting mitigation and adaptation, carbon markets, climate-related innovation, reduced deforestation, subsidy reform, and climate-related risk disclosure can spur companies, investors, and others to address climate risk (Ch. 19). Public sector policies and frameworks to incentivize greater ambition on mitigation include the 2022 US Inflation Reduction Act (IRA) and the EU's Carbon Border Adjustment Mechanism (CBAM), adopted in May 2023. The CBAM may impose costs for US exporters to Europe and spark retaliatory measures by others, with spillover impacts for US exporters to other regions.[119,120] Although domestically oriented, the IRA may spur investment by US companies in renewable energy and other technologies that could be applied to international markets.

Investors and companies increasingly view climate change mitigation as a business necessity and an opportunity.[108,121,122,123] From November 2020 to November 2021, the number of companies worldwide committing to reducing their carbon footprint to "net zero" through emissions reductions, carbon capture, and emissions offsets by 2050 or sooner had grown from 30 to more than 450, and the value of assets represented multiplied 26 times.[124]

The value of global carbon offset trading quadrupled from 2018 to 2021.[125] The Paris Agreement Article 6 rule book, adopted in 2021, creates global norms for government carbon trading and is expected to inform private transactions.[126,127,128] A maturing carbon offset market is projected to grow 15-fold by 2030 and 100-fold by 2050, presenting opportunities for US firms to meet mitigation goals through overseas investments and the potential to generate resources to support local adaptation measures.[129,130,131,132] There remain concerns that carbon trading could shift burdens onto developing countries, vulnerable communities, and future generations.[133,134]

A growing number of investors and asset owners have committed to evaluate and disclose climate risks. As of September 2022, 3,400 organizations from 95 countries have supported the Task Force on Climate-Related Financial Disclosures, representing nearly all economic sectors.[135] Banks, insurance

companies, and pension regulators are focusing on climate-related risks.[136,137,138] The US Securities and Exchange Commission has proposed mandatory climate financial risk disclosure, paralleling similar actions by the United Kingdom and others.[139,140]

Despite growing corporate interest in addressing climate change, implementation lags behind commitments to climate risk disclosure and net-zero goals. Pressure is growing to convert these commitments into credible measurable actions, including through science-based targets.[113,141,142,143,144] Small- and medium-sized enterprises may face challenges navigating complex reporting standards, which could impact their competitiveness and access to financing.[145] Increased climate risk disclosure may increase costs and discourage US investment in vulnerable areas.[146]

Despite historic challenges, increased awareness of risks and market opportunities has begun to generate interest in private investment in adaptation. Private-sector adaptation investment has begun to be tracked alongside public climate adaptation finance, although less than $500 million was identified in 2021.[117] Institutional investors have begun to develop frameworks for investing in climate adaptation and resilience opportunities.[147] The Adaptation Solutions Taxonomy, peer-reviewed and released in 2020, identifies companies supporting adaptation and climate resilience solutions.[148] The first private investment fund secured $185 million for climate resilience and adaptation technologies in 2022.[149]

While government regulations, expenditures, and market-driven climate responses are key to creating enabling environments for climate responses, they can also increase corruption risks, which in turn can undermine business efficiency, frustrate the effectiveness of climate responses, and exacerbate insecurity or poor governance.[59,60] Thus, enabling environments to ensure transparent, accountable, and participatory climate responses may impact the balance of risks and opportunities for US businesses and economic interests.[150,151,152]

## Key Message 17.4

## Climate Change Undermines Sustainable Development

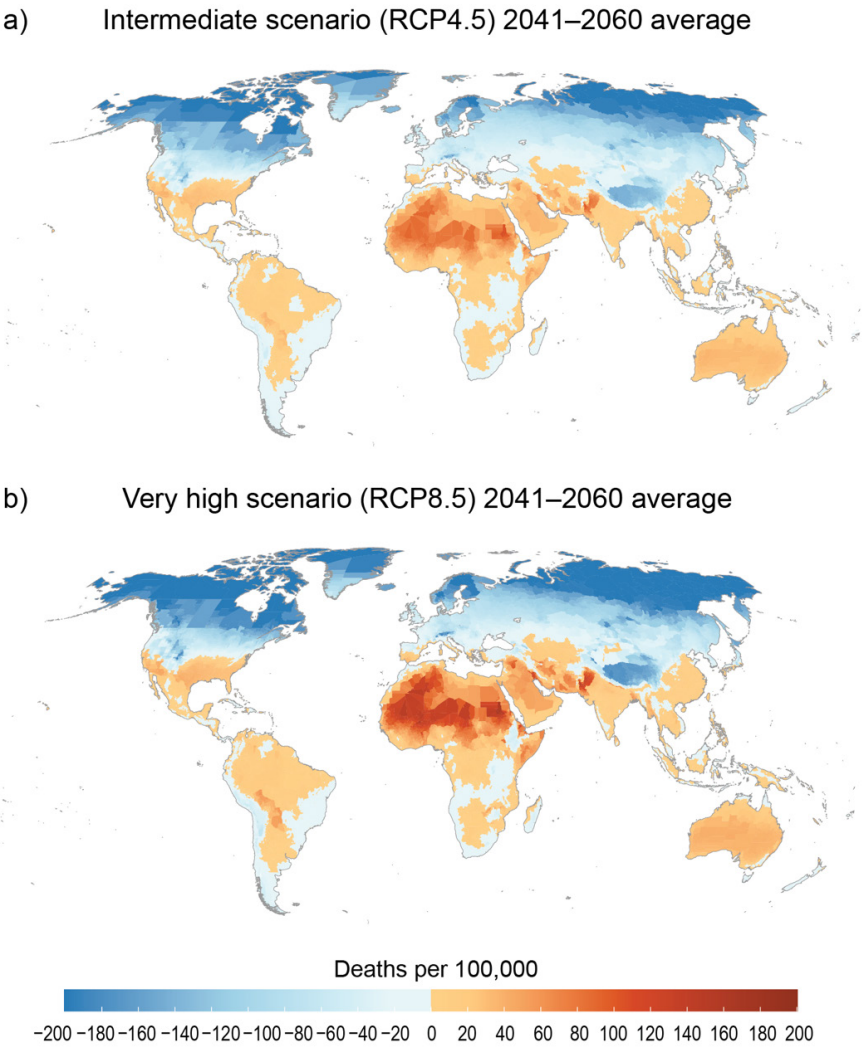
Climate change undermines the world's ability to develop sustainably, reverses development gains, and exacerbates inequities (*very likely*, *high confidence*). Climate finance is increasing, but global flows continue to fall short of needs (*likely*, *high confidence*). Accelerated deployment of adaptation and mitigation action at scale can yield substantial benefits for sustainable development (*likely*, *medium confidence*). Climate action is most effective when co-developed and grounded in equity, local ownership, and inclusive governance (*likely*, *medium confidence*).

The impacts of climate change are globally pervasive, touching all aspects of human, built, and natural systems, including food security, poverty, health, water, infrastructure, and education, among others. Climate change is a risk multiplier in the face of existing development challenges, such as a rapidly growing population base; increased migration, particularly to urban centers, and displacement; increased food insecurity; and rising energy demands. These development challenges are also hampered by reductions in the capacity of natural resources and landscapes to buffer against increased risks, an inability of lifeline services to keep pace with needs, limited economic diversification, low educational levels, and weak institutions to manage these changes.[153] In conjunction with these and other factors (Figures 17.1, 17.2), climate change undermines sustainable development, reversing the significant development gains made in recent decades.[154,155,156,157] These challenges highlight the need to take into account the impacts

of climate in development trajectories in order to inform mitigation and adaptation response to achieve sustainable development.[158,159,160]

Globally, an estimated 26 million people are falling into poverty every year due to extreme weather events such as floods and droughts, and projections point to millions more that could be pushed into poverty by midcentury due to climate change.[153,161] Climate change impacts fall disproportionately on low-income countries and on marginalized and underrepresented populations, which have fewer resources to adapt. Figure 17.5 shows the differential mortality risks from climate change around the world, which results in unequal distribution of risk between and within countries. Limited resources, response capacities, and geophysical and socioeconomic constraints can reduce the feasibility of adaptation.[162,163,164,165] In some contexts, impacts will be beyond the ability of communities to adapt (Ch. 31).[2] This raises equity concerns, particularly given the relatively small greenhouse gas contributions of many low-income populations.[166,167]

## Impact of Climate Change on Mortality Rates in 2050




**Climate change will exacerbate global inequalities in mortality rates.**

**Figure 17.5.** A warmer world will interact with existing differential capacities, shifting mortality patterns. Even when accounting for future adaptation and rising incomes, mortality will significantly increase in the Global South. The maps show projected changes in mortality due to climate change in 2050 (averaged over 2041–2060) for (**a**) an intermediate scenario (RCP4.5) and (**b**) a very high scenario (RCP8.5). Adapted with permission from Carleton et al. 2020.[168]

Despite growing climate financing, global finance flows continue to fall short of mitigation and adaptation goals and needs.[2,117] To avoid the most dangerous impacts of climate change, annual international climate finance flows in support of adaptation and mitigation efforts would need to increase by 3 to 6 times from current levels by 2030.[2] Even if mitigation finance goals were met, adaptation finance and the resulting percentage of climate finance toward adaptation would need to increase as well.[169] Adaptation costs for developing countries alone are projected to be $140–$300 billion annually by 2030 and $280–$500 billion by 2050 (dollar year not reported), and some estimates go further to propose a doubling or tripling every few years.[107] To date, most adaptation investments have been fragmented, project-based, small-scale, incremental, sector-specific, and more focused on near-term risks and planning.[170] Achieving mitigation and adaptation goals requires alignment of domestic, international, public, and private investment, practices, and business models.[117]

The increasing debt burden many countries incur to manage climate risks and restore economies and livelihoods after extreme events represents a growing obstacle to sustainable development.[153,171] Although large disasters make headlines, globally the cumulative losses from small-scale recurring disasters account for a larger portion of economic losses and erode community resilience.[2] Proactive investments can help safeguard against budget restructuring or reallocations as extreme events become more frequent. For example, investments in early warning systems, flood inundation models, and insurance schemes could have offered protection and limited the long-term effect of the recent floods in Pakistan, where development funds were diverted to disaster response.

Adaptation investments can be affordable, with benefits that far exceed costs not just in terms of financial costs and benefits but also in reduced humanitarian spending, avoided asset losses, and lives and livelihoods saved.[2] The net benefits of investing in mitigation and adaptation include reduced future losses, positive economic outcomes, and social and environmental benefits. Mitigation benefits are expected to exceed costs, even without comprehensive accounting for avoided losses, reduced adaptation needs, and co-benefits, and higher near-term investments are projected to lead to long-term economic gains.[2] The benefits of investing in adaptation across a range of sectors are significant, spanning from $2–$13 for each $1 invested, with some of the higher ranges being associated with investments in infrastructure resilience, early warning and response, and disaster risk management.[172,173,174] Conversely, estimates of the costs of inaction range from a 7% to 14% reduction in global GDP.[101,175]

There is evidence of effective mitigation and adaptation options that are feasible to achieve at scale in specific contexts.[2] Accelerated response to climate change can shift development pathways toward increased sustainable development outcomes despite climate change trajectories. Climate-resilient development efforts are enabled by responses that span policy, diplomacy, public and private investment, and the development and humanitarian assistance domains.[2,176,177,178,179] Increasingly affordable and accessible low-emissions technologies support shifting away from fossil fuels to limit warming.[2] Policy interventions at multiple levels, especially those involving ambitious near-term mitigation targets from current and projected major emitters, can minimize potential for overshooting 1.5°C (2.7°F) warming.[2] Adaptation efforts can reduce disruptions due to shocks and stressors and help countries and people accelerate responsive solutions, aligned with local needs and opportunities, leading to sustainable outcomes, especially for vulnerable populations.[2,180] Internationally, increased coherence and coordination among humanitarian, peace-building, resilience-building, and development can help address convergent risks and opportunities.[181] Participation in international and transboundary climate efforts is shown to result in national and subnational government and civil society action.[169]

Integrated approaches to mitigation and adaptation can further amplify co-benefits of actions.[182] For example, mangrove conservation and restoration, one of many nature-based solutions with mitigation and adaptation outcomes, can minimize the risk of coastal flooding, reduce greenhouse gas emissions, sequester

carbon, and contribute to broader sustainable development benefits related to food security and nutrition, economic prosperity, marine and coastal protection, and natural habitat and biodiversity.[4] Response options also have trade-offs with each other and with various sustainable development goals due to the complex interconnectivity of climate and non-climate risk (Ch. 31). Increased attention to adverse impacts of responses and development pathways can help avoid lock-in of emissions trajectories, maladaptation, and exacerbated inequalities.[2] Further, global momentum and evidence are growing on approaches to accelerate transformative climate actions that embed systems thinking and innovation to facilitate more resilient development pathways.[183,184,185]

Inclusive governance favoring locally led, collaboratively developed responses can strengthen the potential for enabling effective and equitable climate-resilient development outcomes at scale.[26,185] Meaningful engagement of affected groups (including those historically underrepresented and/or marginalized) and the co-development of information and solutions build capacity and increase support for long-term sustainable and equitable response outcomes (KMs 31.1, 32.2).[186,187] Decision-relevant information, and the capacity to use it in novel ways, underpins effective responses.[188,189,190] This information may be global or local and derived from diverse knowledge sources, including the scientific community as well as Traditional Knowledge. Governance and decision-making processes that integrate climate into substantial development efforts and account for the above factors can minimize trade-offs and adverse impacts and result in climate action that advances US interests in broader sustainable development outcomes.[185]

# Traceable Accounts

## *Process Description*

This chapter focuses on the implications of international impacts of climate change on US interests. It does not address or summarize all international impacts of climate change. The topics in the chapter—interdependent climate-related risks; national security; economics, investment, and trade; sustainable development; and climate services—were selected because they represent critical interests that are being affected by climate impacts outside of US borders. Climate effects to these interest areas are context specific and are pervasive across the world. The chapter is limited in terms of providing specific detail due primarily to space constraints and limited literature that specifically addresses climate impacts to US interests.

The authors agree that this points to the lack of a sufficiently timely, policy-oriented, and geographically detailed US Government scientific assessment of climate change outside the US. In addition, current literature does not adequately address or provide evidence on the wide range of response options that could be taken to mitigate impacts. Therefore, US national security and international policymakers and analysts must rely on IPCC assessments, existing academic literature, in-house analysis, or ad hoc contracted studies, which are suboptimal or potentially inconsistent.

Chapter leadership sought an author team that could bring diverse experience, expertise, and perspectives. Care was taken to ensure that the team included both early-career and senior professionals from across government, academia, and the private sector who came from varying geographic areas and personal backgrounds. The authors were selected from the list of individuals who responded to the Federal Register Notice or otherwise directly contacted the US Global Change Research Program (USGCRP) to volunteer. Technical contributors were onboarded to conduct an extensive literature review to further identify any dissensions and help reconcile different inputs. Technical contributors also supported design and development of selected figures. The writing team engaged in conference calls starting in September 2021, and calls continued on a regular basis to discuss content, writing, and technical and logistical issues related to the chapter. The NOAA Technical Support Unit staff joined some of these regular conference calls. Subsets of chapter authors also held conference calls on literature, content, and writing on different sections of the chapter.

Public feedback was sought via Federal Register Notices and a public engagement workshop. During the workshop, the USGCRP and chapter authors shared information about the progress to date of the chapter and sought input from stakeholders to help inform further development of the chapter, as well as to raise general awareness of the process and timeline for the Fifth National Climate Assessment (NCA5).

## Key Message 17.1

## Interdependent, Systemic Climate-Related Risks Increasingly Affect US Interests

### Description of Evidence Base

The literature base on climate change and systemic, interdependent risk has grown significantly since the publication of the Fourth National Climate Assessment (NCA4) in 2018, which looked into transboundary climate risk—that is, how climate impacts in neighboring countries affect US interests. However, the literature on global systemic risks cannot yet be considered expansive; it has evolved from a focus on the

financial sector and has more recently increased—not as a result of climate shocks but rather due to recent supply chain disruptions and the observed ripple effects of COVID-19, which put that interconnectivity into stark relief. According to Li et al. (2021)[19] and Simpson (2021),[20] the existing literature highlights the importance of climate change as a driver of systemic risk, but there is a gap in understanding in terms of the interactions and dynamics that generate risk, the methods to support risk assessment, and the design of adaptation and mitigation responses to address complex risk. There is a lack of evidence surrounding the effectiveness of emerging systems- and scenarios-based approaches that are being designed and implemented to address complex, interdependent risk.[40,46]

### Major Uncertainties and Research Gaps

The literature is evolving from predominantly sector- (e.g., water security, food security) or domain-based (e.g., urban areas) risk assessment toward consideration of complex, interdependent systems that can result in compounding and cascading climate impacts.

There is little available literature that focuses on broad and cascading impacts of interconnected/interdependent climate risks in relation to compounding and cascading effects on multiple US interests. Nor is there a literature base that assesses the performance of approaches and measures to address systemic, interdependent risk.

### Description of Confidence and Likelihood

There is *high confidence* and it is *likely* that in a globally connected world, climate change impacts on US interests are multifaceted, interconnected, and frequently exacerbated by social unrest and environmental degradation. These interconnections and their ripple effects are well documented.

There is *high confidence* and it is *likely* that the scale and speed of climate-related impacts to US interests are expected to increase, due in part to underlying interdependencies and to the projected intensification of climate change. It is unequivocal that climate change is intensifying and that it will result in increased impacts across systems and value chains.

There is *high confidence* and it is *likely* that emerging systems- and scenarios-based approaches to integrative planning are being applied to account for interdependencies and competing priorities. Although these approaches have been developed and are being applied to identify risks and responses, the literature surrounding their effectiveness is less advanced.

## Key Message 17.2

## Climate Change Exacerbates Risks to National Security

### Description of Evidence Base

The literature base on climate change and national security has grown significantly since NCA4, as well as in the approximately 15 years since it became a more prominent focus for scholars and practitioners.[48,53] Given the significant diversity of topics and regions considered for links between climate change and national security, the literature is evolving and cannot yet be considered expansive. Some research questions for which the literature was limited and contested during the NCA4 review period have since seen significant additions and greater agreement among findings, including collaborative research efforts among large groups of scholars. An example of this convergence of findings in recent years involves questions around causal links between select climate impacts and the onset of conflict.[52] Literature on other research questions, such as causal links between climate responses and conflict, is less advanced and more deductive,

often based on historic responses in related issue areas. The number and diversity of US government responses to climate change and national security actions have expanded since the NCA4 review.[49,50]

### Major Uncertainties and Research Gaps

Given the diversity of potential research topics connected to climate change and national security, a number of issue areas and geographies have limited literature using diverse methods. In some cases, data remain limited in scales and locations, which constrains the types of methods that can be utilized. In other instances, the institutional responses to climate change that may have national security implications remain in early stages and therefore do not present an evidence base that could generate research findings with the highest levels of confidence.

### Description of Confidence and Likelihood

There is *high confidence* and it is *likely* that climate change can be a contributing factor to political and social instability and in some instances conflict. There is *high confidence* and it is *very likely* that climate change increasingly impacts the operations and missions of defense, diplomacy, and development agencies and departments critical to US national security. There is *high confidence* and it is *very likely* that defense, diplomacy, and development agencies and departments are increasingly addressing climate impacts and responses across the government. These confidence levels are based on an in-depth review of a robust body of literature drawn from numerous disciplines, as well as a growing set of US Government and international policies, programs, and assessments.

## Key Message 17.3

## Climate Change Presents Risks and Opportunities for US Economics, Trade, and Investments

### Description of Evidence Base

There is significant research on global and regional impacts of acute and chronic climate-mediated risks.[2] There is an emerging body of literature that analyzes economic impacts of these risks on global and regional economies.[85,86] However, studies that draw conclusions regarding macro-level economic impacts of climate change (e.g., Swiss Re 2021[101]) require assumptions regarding the cost of uncertainty that would benefit from peer review and more analysis. The most granular data on the costs of physical climate impacts pertain to acute risks, such as climate-mediated disasters, rather than chronic risks. However, there is debate among scholars on the degree to which the economic effects of acute events are attributable to climate change.[90,91]

Figure 17.3 reflects data reported to EM-DAT, the International Disaster Database on disaster-related events, types, and costs.[191] The categorization of data within this database is dependent on how events are reported, and there may be some discrepancies in how specific events and associated losses are characterized by reporters. For example, EM-DAT captures events and quantifies losses for storm events (including tropical, extratropical, and convective storms) as well as floods (including coastal, riverine, flash, and ice-jam floods). However, EM-DAT does not provide guidance to data reporters for distinguishing flood events from storm events; as a result, damages from floods caused by storm events could potentially be reflected under either "storms" or "floods." However, the purpose of the figure is to show overall trends in event types and damages; the potential for discrepancies in how these events and associated damages are reported in the database is not material to the overall intent of the figure.

A relatively sparse but growing body of literature analyzes economic effects of climate change on sectors or topics in which US economic interests are highly embedded, such as sovereign lending,[98,99]

agriculture,[100,192,193,194] and migration.[195] These studies offer insights from which expected economic impacts on US economics, trade, and investment may be inferred; however, they generally fall short of attempting to quantify isolated impacts to US economic interests.

A growing body of literature from think tanks, consultants, multistakeholder organizations, and institutional sources provides empirical evidence of trends and practices regarding economic risks and opportunities and participation of private-sector interests in climate responses. The literature available in peer-reviewed scientific journals is less extensive than reports and studies available from non-peer-reviewed sources but is growing. Recent literature addresses the impact of corruption on climate responses. However, the most comprehensive and authoritative assessment of corruption risks posed by climate responses derives from a 2011 study.[152]

## Major Uncertainties and Research Gaps

Literature estimating the global and regional economic impacts of physical climate risks, as well as of mitigation and adaptation response choices, is evolving. In addition to more granular analysis of these impacts across different risk categories, gaps in the literature include analysis of how economic impacts outside the US spill over into impacts on US economic, trade, and investment interests. Greater exploration of how policy, regulatory, market, and financial enabling environments mitigate or exacerbate economic, trade, and finance impacts—both at the global and regional levels as well as for US interests—would be valuable. The interrelationship of corruption and climate responses is a topic of emerging relevance that would benefit from updated research and analysis.

## Description of Confidence and Likelihood

There is *high confidence* and it is *very likely* that the physical impacts of climate change are increasingly affecting economic growth at global and regional levels outside of the United States.

There is less authoritative analysis of how these global and regional economic impacts translate into impacts on US economic, trade, and investment interests. Studies of specific areas of economic impact in which US economic interests are highly embedded suggest *likely* implications for US interests, which can be inferred with *medium confidence*.

Similarly, while it is clear that responses by governments and the private sector to climate change will affect the economic impacts of climate change globally and in specific regions and that these responses are expected to translate into both risks and opportunities for US economic, trade, and investment interests, there is a lack of precise analysis attempting to quantify these effects. Consequently, these impacts are assessed as *likely* and with *medium confidence*.

An important mediator of these impacts is the quality and effectiveness of policy, regulatory, market, and financial frameworks that governments and private institutions develop to enable climate change mitigation and adaptation responses. The impact of these enabling environments on US economic, trade, and investment interests is assessed as *likely* and with *medium confidence*.

These confidence levels are based on empirical observation of trends and developments, supplemented with scholarly analysis and significant data relevant to business practice and sentiment reflected in the copious trade literature.

## Key Message 17.4

## Climate Change Undermines Sustainable Development

### Description of Evidence Base

The literature base on climate change, sustainable development, and disaster risk reduction and recovery has grown since NCA4. The literature base is expansive given the diversity of topics, and it is further evolving. Some research questions where the literature was limited and contested during the NCA4 review period have seen significant additions and greater agreement among findings. An example of this convergence can be found in the improved understanding of the importance of interconnectivity of climate and non-climatic impacts on populations and potential effective response options.[185] There has been an increase in literature on the social and economic impacts of climate change and on the implications for poverty and exacerbating inequality.[153,161] Likewise, increasing evidence not only points to the growing need for climate finance and aligning investments for both mitigation and adaptation but also recognizes that while climate finance is increasing, it is not matching or keeping pace with this need. The evidence base on response options has greatly expanded, and the authors have focused on emerging trends and cross-cutting efforts instead of attempting to represent the vast literature on specific response options within various sectors.

### Major Uncertainties and Research Gaps

Given the diversity of potential research topics connected to climate change, sustainable development, and disaster risk reduction and recovery, there is not consistent depth of literature across research topics, geographies, levels (from local to international), and sectors. In some cases, data remain limited in scales and locations, which constrains the types of methods that can be utilized. In other instances, the nature, extent, and effectiveness of responses relative to this section remain in early stages and therefore do not present an evidence base that could generate research findings with the highest levels of confidence. Additionally, the evidence base on the costs and benefits of implementing proactive adaptation strategies is ample but fragmented and very context dependent.

### Description of Confidence and Likelihood

There is *high confidence* and it is *very likely* that climate change undermines the world's ability to develop sustainably, reverses development gains, and exacerbates inequities. Climate change is threatening achievability of the 2030 Sustainable Development Goals, and impacts are *very likely* falling disproportionately on poor, marginalized, and underrepresented populations, and on developing countries in particular, raising equity concerns given that these individuals and countries contributed least to climate change.

There is *high confidence* and it is *likely* that climate finance is increasing, but global flows continue to fall short of needs. There is a significant literature base to support the statements that climate finance is growing but not keeping pace with current needs and that proactive investment is more cost effective than reactive investments.

There is less analysis and evidence regarding the benefits of large-scale mitigation and adaptation action at scale, leading to *medium confidence* and an assessment of *likely* that accelerated deployment of adaptation and mitigation action at scale can yield substantial benefits for sustainable development.

There is *medium confidence* and it is *likely* that climate action is most effective when co-developed and grounded in equity, local ownership, and inclusive governance.

# References


1. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

2. IPCC, 2022: Climate Change 2022: *Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844

3. IPCC, 2018: *Global Warming of 1.5°C. an IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts To Eradicate Poverty*. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157940

4. GCA, 2019: Adapt Now: A Global Call for Leadership on Climate Resilience. Global Commission on Adaptation. https://gca.org/wp-content/uploads/2019/09/GlobalCommission_Report_FINAL.pdf

5. Pulwarty, R., L. Hiebert-Girardet, R.M. Speck, E. Allis, C. Honoré, and J. Stander, 2022: Risk to resilience: Climate change, disasters and the WMO-UNDRR Centre of Excellence. *Bulletin n°*, **71** (1). https://public.wmo.int/en/resources/bulletin/risk-resilience-climate-change-disasters-and-wmo-undrr-centre-of-excellence

6. UNDRR, 2020: *The Human Cost of Disasters: An Overview of the Last 20 Years* (2000–2019). United Nations Office for Disaster Risk Reduction. https://www.undrr.org/publication/human-cost-disasters-overview-last-20-years-2000-2019

7. GAO, 2015: Climate Information: A National System Could Help Federal, State, Local, and Private Sector Decision Makers Use Climate Information. GAO-16-37. U.S. Government Accountability Office, Washington, DC. https://www.gao.gov/assets/gao-16-37.pdf

8. Hewitt, C.D., E. Allis, S.J. Mason, M. Muth, R. Pulwarty, J. Shumake-Guillemot, A. Bucher, M. Brunet, A.M. Fischer, A.M. Hama, R.K. Kolli, F. Lucio, O. Ndiaye, and B. Tapia, 2020: Making society climate resilient: International progress under the global framework for climate services. *Bulletin of the American Meteorological Society*, **101** (2), E237–E252. https://doi.org/10.1175/bams-d-18-0211.1

9. OSTP, 2023: A Federal Framework and Action Plan for Climate Services. White House Office of Science and Technology Policy. https://www.whitehouse.gov/wp-content/uploads/2023/03/ftac_report_03222023_508.pdf

10. IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp. https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/

11. IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Pachauri, R.K. and L.A. Meyer, Eds. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 151 pp. http://ipcc.ch/report/ar5/syr/

12. WMO, 2014: Climate Services for Supporting Climate Change Adaptation. WMO-No. 1170. World Meteorological Organization, Geneva, Switzerland. https://library.wmo.int/doc_num.php?explnum_id=7936

13. Dinku, T., 2019: Ch. 7. Challenges with availability and quality of climate data in Africa. In: *Extreme Hydrology and Climate Variability*. Melesse, A.M., W. Abtew, and G. Senay, Eds. Elsevier, 71–80. https://doi.org/10.1016/b978-0-12-815998-9.00007-5

14. Grossi, A. and T. Dinku, 2022: Enhancing national climate services: How systems thinking can accelerate locally led adaptation. *One Earth*, **5** (1), 74–83. https://doi.org/10.1016/j.oneear.2021.12.007

15. Pulwarty, R.S. and M.V.K. Sivakumar, 2014: Information systems in a changing climate: Early warnings and drought risk management. *Weather and Climate Extremes*, **3**, 14–21. https://doi.org/10.1016/j.wace.2014.03.005

16. UNDRR, 2021: *GAR Special Report on Drought 2021*. United Nations Office for Disaster Risk Reduction, Geneva, Switzerland. https://droughtmanagement.info/literature/UN-GAR_Specia_Report_on_Drought_2021.pdf

17. Vogel, C., A. Steynor, and A. Manyuchi, 2019: Climate services in Africa: Re-imagining an inclusive, robust and sustainable service. *Climate Services*, **15**, 100107. https://doi.org/10.1016/j.cliser.2019.100107

18. WMO, 2020: 2020 State of Climate Services: Risk Information and Early Warning Systems. WMO-No. 1252. World Meteorological Organization, Geneva, Switzerland. https://public.wmo.int/en/resources/library/2020-state-of-climate-services-report

19. Li, H.-M., X.-C. Wang, X.-F. Zhao, and Y. Qi, 2021: Understanding systemic risk induced by climate change. *Advances in Climate Change Research*, **12** (3), 384–394. https://doi.org/10.1016/j.accre.2021.05.006

20. Simpson, N.P., K.J. Mach, A. Constable, J. Hess, R. Hogarth, M. Howden, J. Lawrence, R.J. Lempert, V. Muccione, B. Mackey, M.G. New, B. O'Neill, F.E. Otto, H.-O. Pörtner, A. Reisinger, D. Roberts, D.N. Schmidt, S. Seneviratne, and C.H. Trisos, 2021: A framework for complex climate change risk assessment. *One Earth*, **4** (4), 489–501. https://doi.org/10.1016/j.oneear.2021.03.005

21. Gaupp, F., J. Hall, S. Hochrainer-Stigler, and S. Dadson, 2020: Changing risks of simultaneous global breadbasket failure. *Nature Climate Change*, **10** (1), 54–57. https://doi.org/10.1038/s41558-019-0600-z

22. UNDRR, 2019: Ch. 2. Systemic risks, the Sendai Framework and the 2030 agenda. In: *Global Assessment Report on Disaster Risk Reduction*. United Nations Office for Disaster Risk Reduction, Geneva, Switzerland, 35–73. https://gar.undrr.org/report-2019.html

23. Armstrong McKay, D.I., A. Staal, J.F. Abrams, R. Winkelmann, B. Sakschewski, S. Loriani, I. Fetzer, S.E. Cornell, J. Rockström, and T.M. Lenton, 2022: Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, **377** (6611), 7950. https://doi.org/10.1126/science.abn7950

24. UNDRR, 2022: *Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future*. United Nations Office for Disaster Risk Reduction, Geneva, Switzerland. https://www.undrr.org/gar/gar2022-our-world-risk-gar

25. Hurlbert, M., J. Krishnaswamy, E. Davin, F.X. Johnson, C.F. Mena, J. Morton, S. Myeong, D. Viner, K. Warner, A. Wreford, S. Zakieldeen, and Z. Zommers, 2019: Ch. 7. Risk management and decision making in relation to sustainable development. In: *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Shukla, P.R., J. Skea, E.C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J.P. Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 673–800. https://doi.org/10.1017/9781009157988.009

26. UN Inter-agency Task Force on Financing for Development, 2021: Financing for Sustainable Development Report 2021. United Nations, New York. https://www.un.org/sustainabledevelopment/wp-content/uploads/2022/03/2021-Report.pdf

27. Cheatham, A. and D. Roy, 2022: Central America's Turbulent Northern Triangle. Council on Foreign Relations. https://www.cfr.org/backgrounder/central-americas-turbulent-northern-triangle

28. Shultz, J.M., R.C. Berg, J.P. Kossin, F. Burkle Jr, A. Maggioni, V.A. Pinilla Escobar, M.N. Castillo, Z. Espinel, and S. Galea, 2021: Convergence of climate-driven hurricanes and COVID-19: The impact of 2020 hurricanes Eta and Iota on Nicaragua. *The Journal of Climate Change and Health*, **3**, 100019. https://doi.org/10.1016/j.joclim.2021.100019

29. Sigelmann, L., 2019: The Hidden Driver: Climate Change and Migration in Central America's Northern Triangle. American Security Project, 23 pp. http://www.jstor.org/stable/resrep19824

30. Spencer, N. and M.-A. Urquhart, 2018: Hurricane strikes and migration: Evidence from storms in Central America and the Caribbean. *Weather, Climate, and Society*, **10** (3), 569–577. https://doi.org/10.1175/wcas-d-17-0057.1

31. The White House, 2021: Report on the Impact Of Climate Change on Migration. The White House, Washington, DC, 37 pp. https://www.whitehouse.gov/wp-content/uploads/2021/10/report-on-the-impact-of-climate-change-on-migration.pdf

32. Castellanos, E., M.F. Lemos, L. Astigarraga, N. Chacón, N. Cuvi, C. Huggel, L. Miranda, M.M. Vale, J.P. Ometto, P.L. Peri, J.C. Postigo, L. Ramajo, L. Roco, and M. Rusticucci, 2022: Ch. 12. Central and South America. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, 1689–1816. https://doi.org/10.1017/9781009325844.014

33. Mann, M.E., S. Rahmstorf, K. Kornhuber, B.A. Steinman, S.K. Miller, S. Petri, and D. Coumou, 2018: Projected changes in persistent extreme summer weather events: The role of quasi-resonant amplification. *Science Advances*, **4** (10), 3272. https://doi.org/10.1126/sciadv.aat3272

34. Mbow, C., C. Rosenzweig, L.G. Barioni, T.G. Benton, M. Herrero, M. Krishnapillai, E. Liwenga, P. Pradhan, M.G. Rivera-Ferre, T. Sapkota, F.N. Tubiello, and Y. Xu, 2019: Ch. 5. Food security. In: *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Shukla, P.R., J. Skea, E.C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 437–550. https://doi.org/10.1017/9781009157988.007

35. Brown, M.E., J.M. Antle, P. Backlund, E.R. Carr, W.E. Easterling, M.K. Walsh, C. Ammann, W. Attavanich, C.B. Barrett, M.F. Bellemare, V. Dancheck, C. Funk, K. Grace, J.S.I. Ingram, H. Jiang, H. Maletta, T. Mata, A. Murray, M. Ngugi, D. Ojima, B. O'Neill, and C. Tebaldi, 2015: Climate Change, Global Food Security, and the U.S. Food System. U.S. Department of Agriculture, 146 pp. https://doi.org/10.7930/j0862dc7

36. Hallegatte, S., M. Fay, and E.B. Barbier, 2018: Poverty and climate change: Introduction. *Environment and Development Economics*, **23** (3), 217–233. https://doi.org/10.1017/s1355770x18000141

37. Osendarp, S., G. Verburg, Z. Bhutta, R.E. Black, S.d. Pee, C. Fabrizio, D. Headey, R. Heidkamp, D. Laborde, and M.T. Ruel, 2022: Act now before Ukraine war plunges millions into malnutrition. *Nature*, **604**, 620–624. https://doi.org/10.1038/d41586-022-01076-5

38. Smith, V.H. and J.W. Glauber, 2020: Trade, policy, and food security. *Agricultural Economics*, **51** (1), 159–171. https://doi.org/10.1111/agec.12547

39. Lenton, T.M., S. Benson, T. Smith, T. Ewer, V. Lanel, E. Petykowski, T.W.R. Powell, J.F. Abrams, F. Blomsma, and S. Sharpe, 2022: Operationalising positive tipping points towards global sustainability. *Global Sustainability*, **5**, e1. https://doi.org/10.1017/sus.2021.30

40. Liu, J., H. Mooney, V. Hull, S.J. Davis, J. Gaskell, T. Hertel, J. Lubchenco, K.C. Seto, P. Gleick, C. Kremen, and S. Li, 2015: Sustainability. Systems integration for global sustainability. *Science*, **347** (6225), 1258832. https://doi.org/10.1126/science.1258832

41. Hill, A., D. Mason, J.R. Potter, M. Hellmuth, B. Ayyub, and J.W. Baker, 2019: Ready for Tomorrow: Seven Strategies for Climate-Resilient Infrastructure. Hoover Institution. https://www.hoover.org/research/ready-tomorrow-seven-strategies-climate-resilient-infrastructure

42. Morchain, D., 2021: Progress and Challenges in Achieving Vertical Integration in Adaptation Processes. NAP Global Network. https://napglobalnetwork.org/wp-content/uploads/2021/09/napgn-en-2021-vertical-integration-in-adaptation-processes.pdf

43. Scarlett, L. and M. McKinney, 2016: Connecting people and places: The emerging role of network governance in large landscape conservation. *Frontiers in Ecology and the Environment*, **14** (3), 116–125. https://doi.org/10.1002/fee.1247

44. Shames, S. and S.J. Scherr, 2019: Achieving Climate Change Adaptation Through Integrated Landscape Management. Global Commission on Adaptation, Rotterdam, Netherlands and Washington, DC, USA. https://gca.org/reports/achieving-climate-change-adaptation-through-integrated-landscape-management/

45. Ziervogel, G., P. Satyal, R. Basu, A. Mensah, C. Singh, S. Hegga, and T.Z. Abu, 2019: Vertical integration for climate change adaptation in the water sector: Lessons from decentralisation in Africa and India. *Regional Environmental Change*, **19** (8), 2729–2743. https://doi.org/10.1007/s10113-019-01571-y

46. Garcia, C.A., S. Savilaakso, R.W. Verburg, N. Stoudmann, P. Fernbach, S.A. Sloman, G.D. Peterson, M.B. Araújo, J.-F. Bastin, J. Blaser, L. Boutinot, T.W. Crowther, H. Dessard, A. Dray, S. Francisco, J. Ghazoul, L. Feintrenie, E. Hainzelin, F. Kleinschroth, B. Naimi, I.P. Novotny, J. Oszwald, S.A. Pietsch, F. Quétier, B.E. Robinson, M. Sassen, P. Sist, T. Sunderland, C. Vermeulen, L. Wilmé, S.J. Wilson, F. Zorondo-Rodríguez, and P.O. Waeber, 2022: Strategy games to improve environmental policymaking. *Nature Sustainability*, **5** (6), 464–471. https://doi.org/10.1038/s41893-022-00881-0

47. Ringsmuth, A.K., I.M. Otto, B. van den Hurk, G. Lahn, C.P.O. Reyer, T.R. Carter, P. Magnuszewski, I. Monasterolo, J.C.J.H. Aerts, M. Benzie, E. Campiglio, S. Fronzek, F. Gaupp, L. Jarzabek, R.J.T. Klein, H. Knaepen, R. Mechler, J. Mysiak, J. Sillmann, D. Stuparu, and C. West, 2022: Lessons from COVID-19 for managing transboundary climate risks and building resilience. *Climate Risk Management*, **35**, 100395. https://doi.org/10.1016/j.crm.2022.100395

48. Busby, J.W., 2022: The politics of climate change. In: *States and Nature: The Effects of Climate Change on Security*. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/9781108957922

49. DOD, 2021: Department of Defense Climate Risk Analysis. Report Submitted to National Security Council. U.S. Department of Defense, Office of the Undersecretary for Policy, 18 pp. https://media.defense.gov/2021/oct/21/2002877353/-1/-1/0/dod-climate-risk-analysis-final.pdf

50. NIC, 2021: Climate Change and International Responses Increasing Challenges to US National Security Through 2040. NIC-NIE-2021-10030-A. National Intelligence Council. https://www.dni.gov/files/ODNI/documents/assessments/NIE_Climate_Change_and_National_Security.pdf

51. Abel, G.J., M. Brottrager, J. Crespo Cuaresma, and R. Muttarak, 2019: Climate, conflict and forced migration. *Global Environmental Change*, **54**, 239–249. https://doi.org/10.1016/j.gloenvcha.2018.12.003

52. Mach, K.J., C.M. Kraan, W.N. Adger, H. Buhaug, M. Burke, J.D. Fearon, C.B. Field, C.S. Hendrix, J.-F. Maystadt, J. O'Loughlin, P. Roessler, J. Scheffran, K.A. Schultz, and N. von Uexkull, 2019: Climate as a risk factor for armed conflict. *Nature*, **571** (7764), 193–197. https://doi.org/10.1038/s41586-019-1300-6

53. von Uexkull, N. and H. Buhaug, 2021: Security implications of climate change: A decade of scientific progress. *Journal of Peace Research*, **58** (1), 3–17. https://doi.org/10.1177/0022343320984210

54. Daoudy, M., J. Sowers, and E. Weinthal, 2022: What is climate security? Framing risks around water, food, and migration in the Middle East and North Africa. *WIREs Water*, **9** (3), e1582. https://doi.org/10.1002/wat2.1582

55. Dumaine, C., 2022: Adapting to new security realities in a climate-disrupted world. *The Journal of Intelligence, Conflict, and Warfare*, **4** (3), 98–104. https://doi.org/10.21810/jicw.v4i3.4155

56. UNDP, 2022: Special Report: New Threats to Human Security in the Anthropocene: Demanding Greater Solidarity. United Nations Development Programme, New York, NY. https://hs.hdr.undp.org/pdf/srhs2022.pdf

57. Sitati, A., E. Joe, B. Pentz, C. Grayson, C. Jaime, E. Gilmore, E. Galappaththi, A. Hudson, G.N. Alverio, K.J. Mach, M. van Aalst, N. Simpson, P.N. Schwerdtle, S. Templeman, Z. Zommers, I. Ajibade, L.S.S. Chalkasra, P. Umunay, I. Togola, A. Khouzam, G. Scarpa, E.C. de Perez, and Global Adaptation Mapping Initiative Team, 2021: Climate change adaptation in conflict-affected countries: A systematic assessment of evidence. *Discover Sustainability*, **2** (1), 42. https://doi.org/10.1007/s43621-021-00052-9

58. Asaka, J.O., 2021: Climate change-terrorism nexus? A preliminary review/analysis of the literature. *Perspectives on Terrorism*, **15** (1), 81–92. https://www.jstor.org/stable/26984799

59. Erickson, C., 2020: The climate-corruption connection. *Harvard Political Review*. https://harvardpolitics.com/the-climate-corruption-connection/

60. Nest, M., S. Mullard, and C. Wathne, 2020: Corruption and Climate Finance: Implications for Climate Change Interventions. U4 Brief 2020:14. U4 Anti-Corruption Resource Centre, Chr. Michelsen Institute. https://www.u4.no/publications/corruption-and-climate-finance

61. NIC, 2021: Global Trends 2040: A More Contested World. NIC 2021-02339. National Intelligence Council. https://www.dni.gov/files/ODNI/documents/assessments/GlobalTrends_2040.pdf

62. Busby, J.W., 2021: Beyond internal conflict: The emergent practice of climate security. *Journal of Peace Research*, **58** (1), 186–194. https://doi.org/10.1177/0022343320971019

63. Hermans, K. and R. McLeman, 2021: Climate change, drought, land degradation and migration: Exploring the linkages. *Current Opinion in Environmental Sustainability*, **50**, 236–244. https://doi.org/10.1016/j.cosust.2021.04.013

64. UNGA, 2018: Global Compact for Safe, Orderly and Regular Migration: Intergovernmentally Negotiated and Agreed Outcome. United Nations General Assembly, 34 pp. https://refugeesmigrants.un.org/sites/default/files/180713_agreed_outcome_global_compact_for_migration.pdf

65. OSTP, 2023: Congressionally-mandated report on solar radiation modification. White House Office of Science and Technology Policy, Washington, DC, June 30, 2023. https://www.whitehouse.gov/ostp/news-updates/2023/06/30/congressionally-mandated-report-on-solar-radiation-modification/

66. Biermann, F., J. Oomen, A. Gupta, S.H. Ali, K. Conca, M.A. Hajer, P. Kashwan, L.J. Kotzé, M. Leach, D. Messner, C. Okereke, Å. Persson, J. Potočnik, D. Schlosberg, M. Scobie, and S.D. VanDeveer, 2022: Solar geoengineering: The case for an international non-use agreement. *WIREs Climate Change*, **13** (3), e754. https://doi.org/10.1002/wcc.754

67. Reynolds, J.L., 2019: Solar geoengineering to reduce climate change: A review of governance proposals. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **475** (2229), 20190255. https://doi.org/10.1098/rspa.2019.0255

68. Abrahams, D. and E.R. Carr, 2017: Understanding the connections between climate change and conflict: Contributions from geography and political ecology. *Current Climate Change Reports*, **3** (4), 233–242. https://doi.org/10.1007/s40641-017-0080-z

69. Krampe, F., E.S. Smith, and M.D. Hamidi, 2021: Security implications of climate development in conflict-affected states: Implications of local-level effects of rural hydropower development on farmers in Herat. *Political Geography*, **90**, 102454. https://doi.org/10.1016/j.polgeo.2021.102454

70. Dabelko, G.D., A. Barnhoorn, N. Bell, D. Bell-Moran, E. Broek, A. Eberlein, A. Gadnert, E. Remling, J. Staudenmann, C. Bogner, K. Eklöw, B. Horn, and K. Kim, 2022: Navigating a Just and Peaceful Transition: Environment of Peace (Part 3). SIPRI, Stockholm, Sweden. https://doi.org/10.55163/bhyr7656

71. Scholten, D., M. Bazilian, I. Overland, and K. Westphal, 2020: The geopolitics of renewables: New board, new game. *Energy Policy*, **138**, 111059. https://doi.org/10.1016/j.enpol.2019.111059

72. The White House, 2021: Executive Order on America's Supply Chains. The White House, Washington, DC. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/

73. Church, C. and A. Crawford, 2020: Ch. 12. Minerals and the metals for the energy transition: Exploring the conflict implications for mineral-rich, fragile states. In: *The Geopolitics of the Global Energy Transition*. Hafner, M. and S. Tagliapietra, Eds. Springer, Cham, Switzerland, 279–304. https://doi.org/10.1007/978-3-030-39066-2_12

74. USGS, 2022: Mineral Commodity Summaries 2022. U.S. Geological Survey, 202 pp. https://doi.org/10.3133/mcs2022

75. Humphries, M., 2019: Critical Minerals and U.S. Public Policy. CRS Report R45810. Congressional Research Service. https://crsreports.congress.gov/product/pdf/r/r45810

76. DHS, 2021: DHS Strategic Framework for Addressing Climate Change. U.S. Department of Homeland Security. https://www.dhs.gov/publication/dhs-strategic-framework-addressing-climate-change

77. DOD, 2021: Department of Defense Climate Adaptation Plan. Report Submitted to National Climate Task Force and Federal Chief Sustainability Officer. U.S. Department of Defense, Office of the Undersecretary of Defense. https://www.sustainability.gov/pdfs/dod-2021-cap.pdf

78. DOS, 2021: Climate Adaptation and Resilience Plan. U.S. Department of State, 19 pp. https://www.sustainability.gov/pdfs/state-2021-cap.pdf

79. USAID, 2022: Climate Strategy 2022–2030. U.S. Agency for International Development. https://www.usaid.gov/policy/climate-strategy

80. Pinson, A.O., K.D. White, S.A. Moore, S.D. Samuelson, B.A. Thames, P.S. O'Brien, C.A. Hiemstra, P.M. Loechl, and E.E. Ritchie, 2020: Army Climate Resilience Handbook. U.S. Army Corps of Engineers, Washington, DC. https://www.asaie.army.mil/public/es/doc/army_climate_resilience_handbook_change_1.pdf

81. Burnett, M. and K.J. Mach, 2021: A "precariously unprepared" Pentagon? Climate security beliefs and decision-making in the U.S. military. *Global Environmental Change*, **70**, 102345. https://doi.org/10.1016/j.gloenvcha.2021.102345

82. Garfin, G., D.A. Falk, C.D. O'Connor, K. Jacobs, R.D. Sagarin, A.C. Haverland, A. Haworth, A. Baglee, J. Weiss, J. Overpeck, and A.A. Zuñiga-Terán, 2021: A new mission: Mainstreaming climate adaptation in the US Department of Defense. *Climate Services*, **22**, 100230. https://doi.org/10.1016/j.cliser.2021.100230

83. Samaras, C., W.J. Nuttall, and M. Bazilian, 2019: Energy and the military: Convergence of security, economic, and environmental decision-making. *Energy Strategy Reviews*, **26**, 100409. https://doi.org/10.1016/j.esr.2019.100409

84. DOD, 2019: Report to Congress: Department of Defense Arctic Strategy. U.S. Department of Defense, Office of the Under Secretary of Defense for Policy. https://media.defense.gov/2019/jun/06/2002141657/-1/-1/1/2019-dod-arctic-strategy.pdf

85. Burke, M., S.M. Hsiang, and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527** (7577), 235–239. https://doi.org/10.1038/nature15725

86. Diffenbaugh, N.S. and M. Burke, 2019: Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (20), 9808–9813. https://doi.org/10.1073/pnas.1816020116

87. AON, 2021: 2021 Weather, Climate and Catastrophe Insight. AON. https://www.aon.com/getmedia/1b516e4d-c5fa-4086-9393-5e6afb0eeded/20220125-2021-weather-climate-catastrophe-insight.pdf.aspx

88. Bevere, L. and F. Remondi, 2022: Natural Catastrophes in 2021: The Floodgates are Open. Swiss Re Institute, Zurich, Switzerland. https://www.swissre.com/institute/research/sigma-research/sigma-2022-01.html

89. WMO, 2021: WMO Atlas of Mortality and Economic Losses From Weather, Climate and Water Extremes (1970–2019). WMO-No. 1267. World Meteorological Organization, Geneva, Switzerland. https://library.wmo.int/index.php?lvl=notice_display&id=21930#.y437p-zmjpq

90. Botzen, W.J.W., F. Estrada, and R.S.J. Tol, 2021: Methodological issues in natural disaster loss normalisation studies. *Environmental Hazards*, **20** (2), 112–115. https://doi.org/10.1080/17477891.2020.1830744

91. Pielke, R., 2021: Economic 'normalisation' of disaster losses 1998–2020: A literature review and assessment. *Environmental Hazards*, **20** (2), 93–111. https://doi.org/10.1080/17477891.2020.1800440

92. Basel Committee on Banking Supervision, 2021: Climate-Related Risk Drivers and Their Transmission Channels. Bank for International Settlements. https://www.bis.org/bcbs/publ/d517.pdf

93. IMPAX Asset Management, 2020: Physical Climate Risks: Designing a Resilient Response to the Inevitable Impact of Climate Change. IMPAX Asset Management Group, 18 pp. https://impaxam.com/wp-content/uploads/2020/09/20200924_physical_climate_risk.pdf

94. Schinko, T., L. Drouet, Z. Vrontisi, A. Hof, J. Hinkel, J. Mochizuki, V. Bosetti, K. Fragkiadakis, D. van Vuuren, and D. Lincke, 2020: Economy-wide effects of coastal flooding due to sea level rise: A multi-model simultaneous treatment of mitigation, adaptation, and residual impacts. *Environmental Research Communications*, **2** (1), 015002. https://doi.org/10.1088/2515-7620/ab6368

95. Statista, 2023: Foreign Direct Investment Position of the United States Abroad from 2000 to 2022. Statista. https://www.statista.com/statistics/188571/united-states-direct-investments-abroad-since-2000/

96. U.S. Census Bureau, 2023: Annual 2022 Press Highlights. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/foreign-trade/statistics/highlights/AnnualPressHighlights.pdf

97. BEA, 2023: Table 1. U.S. International Trade in Goods and Services: Exports, Imports, and Balances. U.S. Department of Commerce, Bureau of Economic Analysis. https://www.bea.gov/sites/default/files/2023-09/trad-time-series-0723.xlsx

98. Mallucci, E., 2020: Natural Disasters, Climate Change, and Sovereign Risk. International Finance Discussion Papers 1291r1. Board of Governors of the Federal Reserve System, Washington, DC. https://doi.org/10.17016/ifdp.2020.1291r1

99. Phan, T. and F.F. Schwartzman, 2023: Climate Defaults and Financial Adaptation. Working Paper No. 23-06. Federal Reserve Bank of Richmond. https://doi.org/10.21144/wp23-06

100. Liefert, W.M., L. Mitchell, and R. Seeley, 2021: Economic Crises in Foreign Markets Reduce U.S. Agricultural Exports. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/amber-waves/2021/april/economic-crises-in-foreign-markets-reduce-us-agricultural-exports/

101. Swiss Re, 2021: The Economics of Climate Change: No Action Not an Option. Swiss Re Institute. https://www.swissre.com/dam/jcr:e73ee7c3-7f83-4c17-a2b8-8ef23a8d3312/swiss-re-institute-expertise-publication-economics-of-climate-change.pdf

102. Cruz, J.-L. and E. Rossi-Hansberg, 2021: The Economic Geography of Global Warming. NBER Working Paper No. 28466. National Bureau of Economic Research. https://doi.org/10.3386/w28466

103. Semieniuk, G., E. Campiglio, J.-F. Mercure, U. Volz, and N.R. Edwards, 2021: Low-carbon transition risks for finance. *WIREs Climate Change*, **12** (1), e678. https://doi.org/10.1002/wcc.678

104. OECD, 2018: Climate-Resilient Infrastructure. OECD Environment Policy Paper No. 14. Organisation for Economic Co-Operation and Development. https://www.oecd.org/environment/cc/policy-perspectives-climate-resilient-infrastructure.pdf

105. Bland, R., A. Granskog, and T. Nauclér, 2022: Accelerating Toward Net Zero: The Green Business Building Opportunity. McKinsey Sustainability, 8 pp. https://www.mckinsey.com/capabilities/sustainability/our-insights/accelerating-toward-net-zero-the-green-business-building-opportunity

106. OECD, 2022: *Aggregate Trends of Climate Finance Provided and Mobilised by Developed Countries in 2013–2020. Climate Finance and the USD 100 Billion Goal.* OECD Publishing, Paris, France, 25 pp. https://doi.org/10.1787/d28f963c-en

107. UNEP, 2021: Public-Private Partnerships Could Play Key Role in Combatting Deforestation. United Nations Environment Programme. https://www.unep.org/news-and-stories/story/public-private-partnerships-could-play-key-role-combatting-deforestation

108. IFC, 2016: Climate Investment Opportunities in Emerging Markets: An IFC Analysis. International Finance Corporation, Washington, DC. https://documents1.worldbank.org/curated/en/602971510740408248/pdf/121277-WP-IFC-Climate-Investment-Opportunity-Report-Dec-PUBLIC.pdf

109. GEF, 2019: Advances in Blended Finance: GEF's Solutions to Protect the Global Environment. Global Environment Facility, 24 pp. https://www.thegef.org/publications/advances-blended-finance-gefs-solutions-protect-global-environment

110. Rode, J., A. Pinzon, M.C.C. Stabile, J. Pirker, S. Bauch, A. Iribarrem, P. Sammon, C.A. Llerena, L. Muniz Alves, C.E. Orihuela, and H. Wittmer, 2019: Why 'blended finance' could help transitions to sustainable landscapes: Lessons from the Unlocking Forest Finance project. *Ecosystem Services*, **37**, 100917. https://doi.org/10.1016/j.ecoser.2019.100917

111. TFA, 2022: Forest-Positive Collective Action for Deforestation-Free Commodities Supply Chains. Tropical Forest Alliance, accessed September 8, 2022. https://www.tropicalforestalliance.org/

112. BASE, 2022: The Next-Leap On-Climate: Creating an Enabling Environment for Youth Led Action. BASE. https://energy-base.org/news/the-next-leap-on-climate-creating-an-enabling-environment-for-youth-led-action/

113. Makower, J., 2022: State of Green Business 2022. GreenBiz Group, 51 pp. https://www.greenbiz.com/article/state-green-business-2022

114. Crick, F., K.E. Gannon, M. Diop, and M. Sow, 2018: Enabling private sector adaptation to climate change in sub-Saharan Africa. *WIREs Climate Change*, **9** (2), e505. https://doi.org/10.1002/wcc.505

115. Stenek, V., J.C. Amado, and D. Greenall, 2013: Enabling Environment for Private Sector Adaptation: An Index Assessment Framework. International Finance Corporation, Climate Business Department, Washington, DC. https://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/climate+business/resources/enabling+environment+for+private+sector+adaptation

116. Tall, A., S. Lynagh, C.B. Vecchi, P. Bardouille, F.M. Pino, E. Shabahat, V. Stenek, F. Stewart, S. Power, C. Paladines, P. Neves, and L. Kerr, 2021: Enabling Private Investment in Climate Adaptation & Resilience. World Bank Group and Global Facility for Disaster Reduction and Recovery. https://openknowledge.worldbank.org/entities/publication/6219bf23-87e1-5f30-aaf9-30e0cd793ce3

117. Buchner, B., B. Naran, P. Fernandes, R. Padmanabhi, P. Rosane, M. Solomon, S. Stout, C. Strinati, R. Tolentino, G. Wakaba, Y. Zhu, C. Meattle, and S. Guzmán, 2021: Global Landscape of Climate Finance 2021. Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2021/

118. Naran, B., J. Connolly, P. Rosane, D. Wignarajah, E. Wakaba, and B. Buchner, 2022: Global Landscape of Climate Finance: A Decade of Data 2011–2020. Climate Policy Initiative. https://www.climatepolicyinitiative.org/wp-content/uploads/2022/10/Global-Landscape-of-Climate-Finance-A-Decade-of-Data.pdf

119. European Commission, n.d.: Carbon Border Adjustment Mechanism [Webpage], accessed May 5, 2023. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en

120. Kuusi, T., M. Björklund, V. Kaitila, K. Kokko, M. Lehmus, M. Mehling, T. Oikarinen, J. Pohjola, S. Soimakallio, and M. Wang, 2020: Carbon Border Adjustment Mechanisms and Their Economic Impact on Finland and the EU. Prime Minister's Office, Helsinki, Finland. http://urn.fi/urn:isbn:978-952-287-922-6

121. Climate Action 100+, n.d.: The Business Case [Webpage]. https://www.climateaction100.org/business-case

122. KPMG, 2020: The Business Case for Climate Action. KPMG Sustainable Futures, 28 pp. https://assets.kpmg/content/dam/kpmg/ie/pdf/2020/01/ie-the-business-case-for-climate-action.pdf

123. PPG, 2021: The Business Case for Climate Action. Partners in Project Green. https://partnersinprojectgreen.com/resources/the-business-case-for-climate-action/#the_business_case_for_climate_action

124. GFANZ, 2021: The Glasgow Financial Alliance for Net Zero: Our Progress and Plan Towards a Net-Zero Global Economy. Glasgow Financial Alliance for Net Zero. https://assets.bbhub.io/company/sites/63/2021/11/GFANZ-Progress-Report.pdf

125. Tiseo, I., 2023: Global Carbon Market Size 2018–2021. Statista. https://www.statista.com/statistics/1334848/global-carbon-market-size-value/

126. ADB, 2020: Decoding Article 6 of the Paris Agreement, Version II. Asian Development Bank. https://doi.org/10.22617/tcs200411-2

127. Di Leva, C.E. and S. Vaughan, 2021: The Paris Agreement's New Article 6 Rules: The Promise and Challenge of Carbon Market and Non-market Approaches. International Institute for Sustainable Development. https://www.iisd.org/articles/paris-agreement-article-6-rules

128. IETA, 2023: The Evolving Carbon Credit Market. International Emissions Trading Association. https://www.ieta.org/resources/reports/the-evolving-voluntary-carbon-market-paper/

129. Blaufelder, C., C. Levy, P. Mannion, and D. Pinner, 2021: A Blueprint for Scaling Voluntary Carbon Markets to Meet the Climate Challenge. McKinsey Sustainability, 7 pp. https://www.mckinsey.com/capabilities/sustainability/our-insights/a-blueprint-for-scaling-voluntary-carbon-markets-to-meet-the-climate-challenge

130. EDF and ENGIE Impact, 2021: Trends in the Voluntary Carbon Markets: Where We Are and What's Next. Environmental Defense Fund and ENGIE Impact, 5 pp. https://www.edf.org/content/trends-voluntary-carbon-market-where-we-are-and-whats-next

131. Trove Research, 2021: Future Size of the Voluntary Carbon Market. Trove Research, Harpenden, UK, 10 pp. https://trove-research.com/report/future-size-of-the-voluntary-carbon-market/

132. TSVCM, 2021: Final Report. Taskforce on Scaling Voluntary Carbon Markets. https://www.iif.com/portals/1/files/tsvcm_report.pdf

133. Carton, W., J.F. Lund, and K. Dooley, 2021: Undoing equivalence: Rethinking carbon accounting for just carbon removal. *Frontiers in Climate*, **3**, 664130. https://doi.org/10.3389/fclim.2021.664130

134. Smith, S.M., 2021: A case for transparent net-zero carbon targets. *Communications Earth & Environment*, **2** (1), 24. https://doi.org/10.1038/s43247-021-00095-w

135. TCFD, 2022: Support the TCFD: TCFD Supporters Around the World. Task Force on Climate-Related Financial Disclosures. https://www.fsb-tcfd.org/support-tcfd/

136. FSOC, 2021: Report on Climate-Related Financial Risk. Financial Stability Oversight Council, Washington, DC. https://home.treasury.gov/system/files/261/FSOC-Climate-Report.pdf

137. G7, 2021: Climate and environment ministers' meeting communiqué. *G7 Ministers for Climate and Environment Virtual Meeting*, London, UK, 20–21 May 2021, 27 pp. http://www.g7.utoronto.ca/environment/2021-g7-climate-environment-communique.pdf

138. NGFS, 2021: Guide on Climate-Related Disclosure for Central Banks. Network for Greening the Financial System, 38 pp. https://www.ngfs.net/en/guide-climate-related-disclosure-central-banks

139. SEC, 2022: The Enhancement and Standardization of Climate-Related Disclosures for Investors. Securities and Exchange Commission, 490 pp. https://www.sec.gov/rules/proposed/2022/33-11042.pdf

140. TCFD, 2021: 2021 Status Report. Task Force on Climate-Related Financial Disclosures. https://assets.bbhub.io/company/sites/60/2021/07/2021-TCFD-Status_Report.pdf

141. Bingler, J.A., M. Kraus, M. Leippold, and N. Webersinke, 2022: Cheap talk and cherry-picking: What ClimateBERT has to say on corporate climate risk disclosures. *Finance Research Letters*, **47**, 102776. https://doi.org/10.1016/j.frl.2022.102776

142. Mattison, R., B. Longevialle, B. Bastit, L. Hall, L. Ly, P. Munday, and B. Thomson, 2022: Key Trends That Will Drive the ESG Agenda in 2022. S&P Global. https://www.spglobal.com/esg/insights/featured/special-editorial/key-esg-trends-in-2022

143. SBTi, 2022: Science-Based Net-Zero: Scaling Urgent Corporate Climate Action Worldwide. Science Based Targets Initiative. https://sciencebasedtargets.org/resources/files/SBTiProgressReport2021.pdf

144. The Economist, 2022: A broken system needs urgent repairs. *The Economist*, July 21 2022. https://www.economist.com/special-report/2022/07/21/a-broken-system-needs-urgent-repairs

145. Kinywamaghana, A.B., 2022: Are SMEs ready for ESG reporting? Opportunities and challenges. *Frankfurt School Blog*. Frankfurt School of Finance and Management. https://blog.frankfurt-school.de/are-smes-ready-for-esg-reporting-opportunities-and-challenges/

146. Klusak, P., M. Agarwala, M. Burke, M. Kraemer, and K. Mohaddes, 2021: Rising Temperatures, Falling Ratings: The Effect of Climate Change on Sovereign Creditworthiness. Bennett Institute Working Paper. University of Cambridge, Bennett Institute for Public Policy. https://www.bennettinstitute.cam.ac.uk/publications/rising-temperatures-falling-ratings/

147. IIGCC, 2022: Working Towards a Climate Resilience Investment Framework. Institutional Investors Group on Climate Change, London, UK. https://www.iigcc.org/resources/working-towards-a-climate-resilience-investment-framework

148. Trabacchi, C., J. Koh, S. Shi, and T. Guelig, 2020: Adaptation Solutions Taxonomy. Cabrera, M.M., Ed. Inter-American Development Bank, 69 pp. https://doi.org/10.18235/0002556

149. The Lightsmith Group, 2022: Lightsmith Group Closes Inaugural $186 Million Growth Equity Climate Fund, the First to Focus on Climate Resilience and Adaptation. The Lightsmith Group, New York, NY. https://lightsmithgp.com/news-posts/lightsmith-group-closes-inaugural-186-million-growth-equity-climate-fund-the-first-to-focus-on-climate-resilience-and-adaptation/

150. Anderson, J., 2021: To tackle climate change, take on corruption. *World Bank Blogs*. World Bank Group. https://blogs.worldbank.org/climatechange/tackle-climate-change-take-corruption

151. Sperling, L.I., 2021: Whistleblower protection in a systems approach to sustainable development. *Whistleblower Network News*, December 21, 2021. https://whistleblowersblog.org/opinion/whistleblower-protection-in-a-systems-approach-to-sustainable-development/

152. Sweeney, G., R. Dobson, K. Despota, and D. Zinnbauer, Eds., 2011: *Global Corruption Report: Climate Change*. Transparency International, London, UK and Washington, DC, 400 pp. https://images.transparencycdn.org/images/2011_GCRclimatechange_EN.pdf

153. Birkmann, J., E. Liwenga, R. Pandey, E. Boyd, R. Djalante, F. Gemenne, W.L. Filho, P.F. Pinho, L. Stringer, and D.Wrathall, 2022: Ch. 8. Poverty, livelihoods and sustainable development. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, 1171–1274. https://doi.org/10.1017/9781009325844.010

154. Obersteiner, M., B. Walsh, S. Frank, P. Havlík, M. Cantele, J. Liu, A. Palazzo, M. Herrero, Y. Lu, A. Mosnier, H. Valin, K. Riahi, F. Kraxner, S. Fritz, and D. van Vuuren, 2016: Assessing the land resource–food price nexus of the Sustainable Development Goals. *Science Advances*, **2** (9), e1501499. https://doi.org/10.1126/sciadv.1501499

155. Scobie, M., 2016: Policy coherence in climate governance in Caribbean small island developing states. *Environmental Science & Policy*, **58**, 16–28. https://doi.org/10.1016/j.envsci.2015.12.008

156. Smith, M.R. and S.S. Myers, 2018: Impact of anthropogenic $CO_2$ emissions on global human nutrition. *Nature Climate Change*, **8** (9), 834–839. https://doi.org/10.1038/s41558-018-0253-3

157. Wheeler, T. and J. von Braun, 2013: Climate change impacts on global food security. *Science*, **341** (6145), 508–13. https://doi.org/10.1126/science.1239402

158. Ermolina, M., A. Matveevskaya, and M. Baranuk, 2021: Ch. 20. Climate change and the UN 2030 agenda for sustainable development. In: *Proceedings of Topical Issues in International Political Geography*. Springer, Cham, Switzerland, 226–237. https://doi.org/10.1007/978-3-030-78690-8_20

159. Fuso Nerini, F., B. Sovacool, N. Hughes, L. Cozzi, E. Cosgrave, M. Howells, M. Tavoni, J. Tomei, H. Zerriffi, and B. Milligan, 2019: Connecting climate action with other Sustainable Development Goals. *Nature Sustainability*, **2** (8), 674–680. https://doi.org/10.1038/s41893-019-0334-y

160. Sachs, J., C. Kroll, G. Lafortune, G. Fuller, and F. Woelm, 2022: *Sustainable Development Report 2022*. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/9781009210058

161. Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7** (4), 250–256. https://doi.org/10.1038/nclimate3253

162. Atela, J.O., C.H. Quinn, A.A. Arhin, L. Duguma, and K.L. Mbeva, 2017: Exploring the agency of Africa in climate change negotiations: The case of REDD+. *International Environmental Agreements: Politics, Law and Economics*, **17** (4), 463–482. https://doi.org/10.1007/s10784-016-9329-6

163. Gereke, M. and T. Brühl, 2019: Unpacking the unequal representation of Northern and Southern NGOs in international climate change politics. *Third World Quarterly*, **40** (5), 870–889. https://doi.org/10.1080/01436597.2019.1596023

164. Roger, C. and S. Belliethathan, 2016: Africa in the global climate change negotiations. *International Environmental Agreements: Politics, Law and Economics*, **16** (1), 91–108. https://doi.org/10.1007/s10784-014-9244-7

165. Wunder, S., F. Noack, and A. Angelsen, 2018: Climate, crops, and forests: A pan-tropical analysis of household income generation. *Environment and Development Economics*, **23** (3), 279–297. https://doi.org/10.1017/s1355770x18000116

166. Dooley, K., C. Holz, S. Kartha, S. Klinsky, J.T. Roberts, H. Shue, H. Winkler, T. Athanasiou, S. Caney, E. Cripps, N.K. Dubash, G. Hall, P.G. Harris, B. Lahn, D. Moellendorf, B. Müller, A. Sagar, and P. Singer, 2021: Ethical choices behind quantifications of fair contributions under the Paris Agreement. *Nature Climate Change*, **11** (4), 300–305. https://doi.org/10.1038/s41558-021-01015-8

167. Mattar, S.D., T. Jafry, P. Schröder, and Z. Ahmad, 2021: Climate justice: Priorities for equitable recovery from the pandemic. *Climate Policy*, **21** (10), 1307–1317. https://doi.org/10.1080/14693062.2021.1976095

168. Carleton, T.A., A. Jina, M.T. Delgado, M. Greenstone, T. Houser, S.M. Hsiang, A. Hultgren, R.E. Kopp, K.E. McCusker, I.B. Nath, J. Rising, A. Rode, H.K. Seo, A. Viaene, J. Yuan, and A.T. Zhang, 2020: Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits. Working Paper 27599. National Bureau of Economic Research. https://doi.org/10.3386/w27599

169. IPCC, 2023: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Lee, H. and J. Romero, Eds. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 184 pp. https://doi.org/10.59327/IPCC/AR6-9789291691647

170. O'Neill, B., M. van Aalst, Z. Zaiton Ibrahim, L. Berrang Ford, S. Bhadwal, H. Buhaug, D. Diaz, K. Frieler, M. Garschagen, A. Magnan, G. Midgley, A. Mirzabaev, A. Thomas, and R. Warren, 2022: Ch. 16. Key risks across sectors and regions. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2411–2538. https://doi.org/10.1017/9781009325844.025

171. CFA, 2020: Understanding the Role of Climate Risk Transparency on Capital Pricing for Developing Countries. Findings Report. Climate Finance Advisors, Benefit LLC, Washington, DC. https://climatefinanceadvisors.com/wp-content/uploads/2020/10/FCDO-Report_Findings-Report_11.25.2020.pdf

172. Kornejew, M., J. Rentschler, and S. Hallegatte, 2019: Well Spent: How Governance Determines the Effectiveness of Infrastructure Investments. Policy Research Working Paper 8894. World Bank Group, Washington, DC. https://openknowledge.worldbank.org/handle/10986/31914?locale-attribute=en

173. Richmond, M., J. Choi, P. Rosane, M. Solomon, B. Tonkonogy, D. Molloy, F. Larrain, and J.J. Rae, 2021: Adaptation Finance in the Context of COVID-19. Global Center on Adaptation and Climate Policy Initiative, 64 pp. https://gca.org/wp-content/uploads/2021/01/GCA-Adaption-in-Finance-Report.pdf

174. Williams, S., M. Nitschke, B.Y. Wondmagegn, M. Tong, J. Xiang, A. Hansen, J. Nairn, J. Karnon, and P. Bi, 2022: Evaluating cost benefits from a heat health warning system in Adelaide, South Australia. *Australian and New Zealand Journal of Public Health*, **46** (2), 149–154. https://doi.org/10.1111/1753-6405.13194

175. Philip, P., C. Ibrahim, and C. Hodges, 2022: The Turning Point: A Global Summary. Deloitte. https://www2.deloitte.com/content/dam/Deloitte/global/Documents/gx-global-turning-point-report.pdf

176. Barakat, S. and S. Milton, 2020: Localisation across the humanitarian-development-peace nexus. *Journal of Peacebuilding & Development*, **15** (2), 147–163. https://doi.org/10.1177/1542316620922805

177. Berrang-Ford, L., A.R. Siders, A. Lesnikowski, A.P. Fischer, M.W. Callaghan, et al., 2021: A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, **11** (11), 989–1000. https://doi.org/10.1038/s41558-021-01170-y

178. Peters, K., L. Langston, T. Tanner, and A. Bahadur, 2016: Resilience Across the Post-2015 Frameworks: Towards Coherence. Overseas Development Institute. https://odi.org/en/publications/resilience-across-the-post-2015-frameworks-towards-coherence/

179. Tompkins, E.L., K. Vincent, R.J. Nicholls, and N. Suckall, 2018: Documenting the state of adaptation for the global stocktake of the Paris Agreement. *WIREs Climate Change*, **9** (5), e545. https://doi.org/10.1002/wcc.545

180. Werners, S.E., E. Sparkes, E. Totin, N. Abel, S. Bhadwal, J.R.A. Butler, S. Douxchamps, H. James, N. Methner, J. Siebeneck, L.C. Stringer, K. Vincent, R.M. Wise, and M.G.L. Tebboth, 2021: Advancing climate resilient development pathways since the IPCC's Fifth Assessment Report. *Environmental Science & Policy*, **126**, 168–176. https://doi.org/10.1016/j.envsci.2021.09.017

181. de Carvalho, G., C. de Coning, and L. Connolly, 2014: Creating an Enabling Peacebuilding Environment: How Can External Actors Contribute to Resilience? The African Centre for the Constructive Resolution of Disputes, 9 pp. https://www.accord.org.za/publication/creating-an-enabling-peacebuilding-environment/

182. Spencer, B., J. Lawler, C. Lowe, L. Thompson, T. Hinckley, S.-H. Kim, S. Bolton, S. Meschke, J.D. Olden, and J. Voss, 2017: Case studies in co-benefits approaches to climate change mitigation and adaptation. *Journal of Environmental Planning and Management*, **60** (4), 647–667. https://doi.org/10.1080/09640568.2016.1168287

183. Pelling, M., K. O'Brien, and D. Matyas, 2015: Adaptation and transformation. *Climatic Change*, **133** (1), 113–127. https://doi.org/10.1007/s10584-014-1303-0

184. Saxena, A., K. Qui, and S.-a. Robinson, 2018: Knowledge, attitudes and practices of climate adaptation actors towards resilience and transformation in a 1.5°C world. *Environmental Science & Policy*, **80**, 152–159. https://doi.org/10.1016/j.envsci.2017.11.001

185. Schipper, E.L.F., A. Revi, B.L. Preston, E.R. Carr, S.H. Eriksen, L.R. Fernandez-Carril, B.C. Glavovic, N.J.M. Hilmi, D. Ley, R. Mukerji, M.S.M. de Araujo, R. Perez, S.K. Rose, and P.K. Singh, 2022: Ch. 18. Climate resilient development pathways. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2655–2807. https://doi.org/10.1017/9781009325844.027

186. Leitch, A.M., J.P. Palutikof, D. Rissik, S.L. Boulter, F.N. Tonmoy, S. Webb, A.C.P. Vidaurre, and M.C. Campbell, 2019: Co-development of a climate change decision support framework through engagement with stakeholders. *Climatic Change*, **153** (4), 587–605. https://doi.org/10.1007/s10584-019-02401-0

187. Woodall, L.C., S. Talma, O. Steeds, P. Stefanoudis, M.-M. Jeremie-Muzungaile, and A. de Comarmond, 2021: Co-development, co-production and co-dissemination of scientific research: A case study to demonstrate mutual benefits. *Biology Letters*, **17** (4), 20200699. https://doi.org/10.1098/rsbl.2020.0699

188. Vincent, K., M. Daly, C. Scannell, and B. Leathes, 2018: What can climate services learn from theory and practice of co-production? *Climate Services*, **12**, 48–58. https://doi.org/10.1016/j.cliser.2018.11.001

189. New, M., D. Reckien, D. Viner, C. Adler, S.-M. Cheong, C. Conde, A. Constable, E.C.d. Perez, A. Lammel, R. Mechler, B. Orlove, and W. Solecki, 2022: Ch. 17. Decision-making options for managing risk. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2539–2654. https://doi.org/10.1017/9781009325844.026

190. Singh, C., S. Iyer, M.G. New, R. Few, B. Kuchimanchi, A.C. Segnon, and D. Morchain, 2022: Interrogating 'effectiveness' in climate change adaptation: 11 guiding principles for adaptation research and practice. *Climate and Development*, **14** (7), 650–664. https://doi.org/10.1080/17565529.2021.1964937

191. CRED, 2009: EM-DAT: The International Disaster Database. Centre for Research on the Epidemiology of Disasters, accessed May 5, 2023. https://www.emdat.be/

192. Costinot, A., D. Donaldson, and C. Smith, 2016: Evolving comparative advantage and the impact of climate change in agricultural markets: Evidence from 1.7 million fields around the world. *Journal of Political Economy*, **124** (1), 205–248. https://doi.org/10.1086/684719

193. Gouel, C. and D. Laborde, 2021: The crucial role of domestic and international market-mediated adaptation to climate change. *Journal of Environmental Economics and Management*, **106**, 102408. https://doi.org/10.1016/j.jeem.2020.102408

194. Nath, I., 2021: Climate Change, the Food Problem, and the Challenge of Adaptation through Sectoral Reallocation. Working Paper No. CES-21-29. U.S. Census Bureau, Center for Economic Studies. https://www.census.gov/library/working-papers/2021/adrm/CES-WP-21-29.html

195. Alsina-Pujols, M., 2022: Warming with Borders: Climate Refugees and Carbon Pricing. University of Oslo, Department of Economics. https://www.sv.uio.no/econ/english/research/news-and-events/events/guest-lectures-seminars/job-market/2022/2022-01-25-alsina-pujols.html

Fifth National Climate Assessment: Chapter 18

# Sector Interactions, Multiple Stressors, and Complex Systems

# Chapter 18. Sector Interactions, Multiple Stressors, and Complex Systems

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# Introduction

The Fifth National Climate Assessment assesses the many ways climate change affects people, nature, and infrastructure across the Nation and around the world. The chapters are divided up by sectors and topics, such as water (Ch. 4), food (Ch. 11), economics (Ch. 19), and social justice (Ch. 20). They are also organized by region, from the Northeast (Ch. 21) to Hawai‘i and the US-Affiliated Pacific Islands (Ch. 30).

But in reality, the impacts and risks of climate change unfold across interacting sectors and regions. For example, a forest fire in one region (Ch. 7) can affect air quality (Ch. 14) and human health (Ch. 15) in other regions as well (Chs. 21–30), depending on where winds blow. Further, climate-related hazards interact with multiple stressors that might seem like they have nothing to do with climate change, such as the COVID-19 pandemic, economic recessions, or social inequities. For instance, different households with different levels of wealth can have very different capacities to evacuate in advance of a hurricane or recover if their homes are damaged (Chs. 9, 20, 22, 23).

As a result, if the perspective of only a single sector, topic, or region were considered, many climate impacts might be missed or overlooked. The consequences of climate change would be unexpected and surprising. And at the same time, the prospects for climate responses, whether through adaptation or mitigation, also fundamentally depend on these same interactions across sectors and regions. For example, using water (Ch. 4) for hydropower (Ch. 5) can impact fish in rivers (Ch. 8), as well as water supply for agriculture in rural communities (Ch. 11) and residential use in big cities (Ch. 12). Without considering such types of interactions, climate responses will be less effective, and there could be missed opportunities.

This chapter is about these deep connections inherent to climate impacts, risks, and responses. The chapter considers these interactions and interdependencies across sectors and regions as complex systems that can lead to cascading impacts and sudden failures, as well as sometimes surprising potential for reducing our emissions of heat-trapping gases and preparing for climate risks that can’t be avoided.

The chapter is organized as follows. First, it introduces what we know about complex systems and explains how complex systems—involving interactions across sectors and regions—can lead to climate impacts that happen faster than expected or can limit future options (KM 18.1). Second, the chapter assesses how complex, interacting climate impacts and responses can be most stressful for overburdened communities (KM 18.2). Third, the chapter evaluates how collaborative approaches to generating knowledge about complex systems can lead to better climate responses (KM 18.3). Finally, the chapter considers the degree to which current governance approaches are adequately prepared to handle the complexity of climate change (KM 18.4).

## Key Message 18.1

# Human–Nature Interconnections Create Unexpected Climate Risks and Opportunities

Human–natural systems are dynamic and complex. Interconnected networks of people, infrastructure, commodities, goods, and services influence changing climate risks and are increasingly vulnerable to their impacts (*high confidence*). The vulnerabilities in these networks, and their effects on human–natural systems, strongly depend on human responses and other compounding stressors (*high confidence*). Decision-makers seeking to reduce climate change risks have to navigate diverse and sometimes competing objectives and perspectives across many actors, institutions, and geographic scales while reconciling deep uncertainties and limits to predictability (*high confidence*).

In a changing climate, interconnections among human and natural systems give rise to both successes and failures. For example, power systems can fail if exposed to extreme wind or extreme heat (KM 5.2). When they fail, transportation, water and wastewater treatment, telecommunications, health services, and many other economic activities are also disrupted (KM 19.3).[1,2] The interactions among people, systems (e.g., networks, nature), and sectors thereby transmit opportunities and risks from one to another (e.g., KM 27.4), such as from the power system to the transportation system. These interactions lead to new risks and can both increase and limit existing threats.[3,4,5,6] Figure 18.1 shows six interconnected and overlapping features of human–natural systems; each of these features contributes to the complexity of the systems and influences the effectiveness of climate mitigation and adaptation actions. Box 18.1 illustrates these types of interactions through a specific example, data centers.

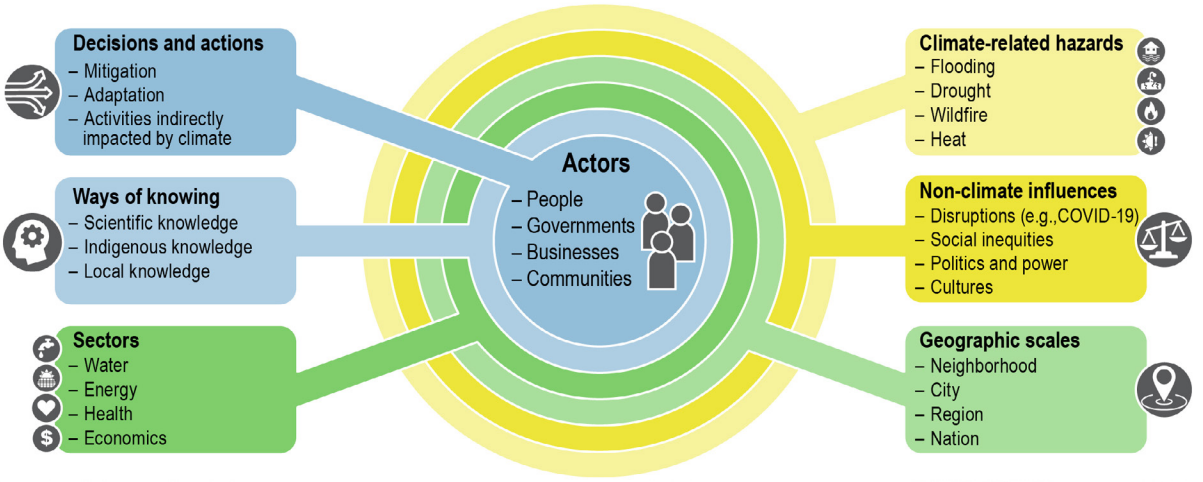
Climate change makes the existing interconnections between human and natural systems more important for two reasons. First, many human and natural systems have conditions in which a small shock or change can produce very large impacts, but these conditions are rarely known in advance.[7] For example, the winter storm in Texas in February 2021 was a relatively brief 10-day shock of extreme cold weather, but it caused cascading failures across many sectors (e.g., energy, water, health), as well as fatalities and long-lived economic impacts for the region and for individuals.[8] There is evidence that warming in the polar north can increase the potential for these types of winter storm shocks in the US.[9] Second, climate change puts natural systems into fundamentally new conditions, so there is a greater chance of experiencing these large potentially negative impacts. Climate change–driven aridification of the American Southwest is an example of a fundamental change that has resulted in more persistent and severe heat as well as drought extremes. The consequences of this fundamental change are complex, increasing the potential for compounding and cascading impacts. These effects include simultaneous increases in the potential risks for human health, disruptions to critical transportation services, stress on power systems, and water scarcity conflicts across regions and sectors.[10,11] The overall risk of bad outcomes increases, and the sources of risk are more complex. There has been substantial progress in the study of complex, adaptive human–natural systems.[3,12,13,14,15,16,17,18] Innovations across many disciplines are helping to address interconnected risks.[19,20,21,22,23,24,25,26] Further, climate mitigation and adaptation actions depend on one another and interact. They both require resilience to intensifying and increasingly complex mixtures of future influences, shocks, and hazards. Figure 18.1 shows how these future influences can be climate-related hazards, such as floods, droughts, or wildfires; environmental shifts, such as changes in forest composition; or social trends or disruptions, such as from changes in economies, political contexts, cultures, or disease.[2,5,12,16,22,23,26,27,28,29] Mitigation and adaptation involve major changes to human–natural systems with global to local implications (KMs 31.1, 32.5). They can create fundamental shifts in supply chains, consumption patterns, technologies,

and competition over constrained natural resources (also see Focus on Risks to Supply Chains).[13,27,30,31,32,33,34] These changes are expected to continue to have disproportionate impacts on exposed populations and ecosystems (KMs 4.2, 5.2, 8.3, 9.3, 15.2).

There are therefore trade-offs, linked benefits, and dependencies among energy transitions, adaptation actions, and sustainability goals (KMs 17.4, 25.4, 31.3, 32.2).[12,15,19,22,28,35,36,37,38,39,40] For example, an increased supply of clean energy helps power air-conditioning to keep homes cool under intensifying heat while also ensuring that this increased energy usage does not cause emissions of heat-trapping gases. This situation also has implications for social equity and justice, as poverty reduction and improved energy security are needed for all households to afford adequate air-conditioning. These interactions demonstrate the importance of accounting for diverse forms of knowledge, social and institutional power dynamics, and justice in navigating risks, challenges, and benefits of interventions and policies (Figure 18.1; KMs 16.3, 17.4, 20.1, 31.3).[31,41,42,43] Recent advances offer promise for assessing risk–benefit trade-offs, interconnections, and sequences of action or inaction across scales.[44,45,46,47] However, rapidly changing human systems, their multisectoral dynamics, and their interconnections with natural systems create deeply uncertain futures. Many futures are possible, and there is disagreement on how probable they are or how they may shape different human–natural systems' responses. Therefore, significant challenges remain for measuring risk–benefit trade-offs when evaluating potential actions.[48,49,50,51]

Recognition of these deep uncertainties and the difficulties in predicting complex interconnections among human and natural systems over long time periods has led to an approach called exploratory systems modeling.[52,53,54] This approach considers diverse scientific perspectives and uses scenarios to better understand a wide array of possible future outcomes. For example, scenarios can examine the consequences of extreme weather conditions that have never previously happened but may happen under a future climate. The approach aims to discover what future conditions, actions, and outcomes are the most consequential.[45,47,55,56,57] Capital investments associated with new energy sources and climate adaptation are both expensive and long-lived. Exploratory modeling of benefits and impacts of these investments can help avoid the unintended amplification of risks and increase future resilience. Exploratory modeling can support adaptation planning by providing a wider array of futures, such as for coastal systems under sea level rise,[58] and by more clearly identifying responses as they occur among interconnected, complex human and natural systems.

## Interacting and Overlapping Features of Human–Natural Systems




**Climate-related experiences and actions connect with many other activities and contexts.**

**Figure 18.1.** Interacting and overlapping features of human–natural systems shape actors' capacities to respond to climate change. The effectiveness of decisions and actions—taken or not (teal center of the figure)—is shaped by multiple other features (outer rings). Ways of knowing (light blue ring), such as local, Indigenous, or scientific knowledge, are a foundation that determines how climate risks and responses are perceived and understood. Moving outward, interactions across sectors (e.g., water and energy) and geographic scales (e.g., from local neighborhoods to the Nation as a whole) determine risks and responses under both climate-related hazards (e.g., flooding, drought, wildfire, and heat) and non-climate influences (e.g., social inequities and cultures). Ultimately, these features together define the complexity inherent to climate risks and responses. Adapted from Brelsford and Jones 2021.[59]

## Box 18.1. Data Centers Create a Critical New Interconnection Between Energy, Water, and the Economy

Data centers are buildings that house large computer systems that support online activities and much of the US economy. There has been rapid growth in the number and size of data centers as the national economy has shifted toward digital communication and activities. Although water and energy use of individual data centers can be difficult to measure precisely,[60] their water and energy footprint is large—accounting for 1.8% of total US electricity usage and 510 million cubic meters of water in 2018—and is an increasing focus of research.[61,62,63] The siting of data centers is a complex problem, influenced by local and state government incentives as well as by land, energy, and water availability to support cooling, such as in climates favoring evaporative cooling. The future demand for data centers, together with their needs for water and energy and their influence on linked water–energy–land systems, will vary considerably geographically.[62] Given that data centers depend on both water and energy and are themselves infrastructure critical for the functioning of the economy, data centers create a new interconnection between energy, water, and the economy.

In the western US, where arid climates are favorable to the evaporative cooling often sought out for data center operations, water and land are inextricably linked through prior-appropriation water law (KM 28.1).[64] As a result, securing adequate supplies of water to support data center demands can become a complex and potentially contentious exercise in acquiring agricultural land and fallowing it, a process that is dependent on state laws governing the transfer of water rights. Moreover, the increasing potential for large-scale, long-term droughts in the western US could lead to unanticipated events (KMs 4.1, 6.1, 28.3). For example, increasingly heavy base-load water consumers such as data centers may make the water system less able to adapt to drought through short-term conservation. Increasing attention to the environmental footprints of new data center projects in the western US potentially signals a new interconnection and potential point of conflict between economic sectors (KM 6.3), such as technological industries versus agriculture.

## Key Message 18.2

## Complex Climate Impacts and Responses Further Burden Frontline Communities

Compounding and cascading interactions among sectors, hazards, and geographies magnify the impact of climate change and societal responses for already-overburdened groups (*high confidence*). However, social vulnerability assessments tend to evaluate risks and impacts by sector, hazard, or jurisdiction, and most complex-systems models do not yet account for social and political dynamics (*high confidence*). Data about how complex systems affect frontline communities under climate change are severely lacking, especially for hard-to-reach populations, and this can lead to disproportionate risks and impacts for these groups (*high confidence*).

The complex systems described in KM 18.1 can create cascading and compounding climate impacts that particularly affect people and communities with little flexibility to absorb additional stress. This includes smaller and more rural communities, lower-income households, racialized minorities, people with health conditions and disabilities, pregnant people, caregivers, young children, and older adults (KMs 4.2, 15.2, 16.2).[18,65,66,67,68,69,70,71] The combination of complex societal factors (Figure 18.1) with people's multiple roles and identities shapes their lived experiences of multiple shocks and stressors (Figure 18.2).[72,73,74] It is not an accident that access to land, housing, infrastructure, food, and water in the US is highly unequal.[67,75] Within a context of institutionalized inequality and uneven access to safe housing and quality infrastructure, new and conflicting private- and public-sector responses to complex climatic and non-climate events often reinforce existing inequities.[18] At the same time, each person carries multiple identities and plays multiple roles, creating intersectional vulnerabilities that can intensify direct impacts of climate change and indirect impacts of climate actions by more privileged groups. For instance, in rural Alaska, climate change is rendering more difficult the lives of Iñupiat women as they care for multiple generations, maintain land-based food and cultural systems, and endure gender-based violence,[76] while young, single men working in the oil and gas industry are experiencing the energy transition very differently.

Increased exposure to flooding provides an example of how compounding and cascading interactions and intersectional vulnerabilities can amplify harm in already-burdened communities. Legacies of inequitable access to residential home loans, municipal incorporation to isolate wealth in suburbs, and infrastructure investments that privileged certain neighborhoods and municipalities over others have concentrated low-income people, African Americans, and other frontline communities in places with high flood risk.[77,78,79,80] Federal flood risk response programs privilege predominantly White and wealthier communities by giving them more funding for levees or seawalls.[81] These measures worsen downstream or down-coast flooding in places that might not be able to afford such infrastructure.[80] Federal programs also disproportionately fund predominantly White communities to voluntarily relocate from floodplains (Figure 20.3),[82,83,84] while low-income people, including renters, receive less assistance and have to move farther away to places with fewer amenities.[85] Box 18.2 shows a different example of how cascading and compounding events can worsen long-standing inequities. It discusses how a wildfire exacerbated social conflict over land, housing, and infrastructure in California. Accordingly, people's cumulative vulnerability can be understood and addressed only through multiple scales of analysis (e.g., Turek-Hankins et al. 2020[86]) and through integrated strategies for housing, planning, social services, lending, and racial justice.

Models of how climate impacts affect complex systems and how societies can respond usually do not account for people's diverse roles, identities, and lived experiences nor the social, political, and governance

characteristics of decision-making.[3,87,88,89,90] For example, political polarization, in addition to structural inequities, increasingly shapes individual and government responses to disasters and long-term planning.[91,92] This can lead to a patchwork of mitigation and adaptation efforts across a region, which can weaken overall system function.[93,94,95] Data gaps exacerbate the modeling uncertainties described in Key Message 18.1, especially for smaller, less studied urban, suburban, and rural areas and Indigenous communities (KMs 11.3, 16.2).[69,96,97] Research on the linkages between places, such as how impacts on agriculture systems affect urban food security, migration, and housing demand, is also limited (KM 11.2).[98] The absence of research on the lived experiences, climate impacts and risks, and implementation outcomes for overburdened communities often leads to their underrepresentation in decision-making.[99] Accounting for people's diverse roles and identities, modeling social and political responses to climate change, and improving data availability can improve the modeling of complex systems and the inclusivity of decision-making tools.

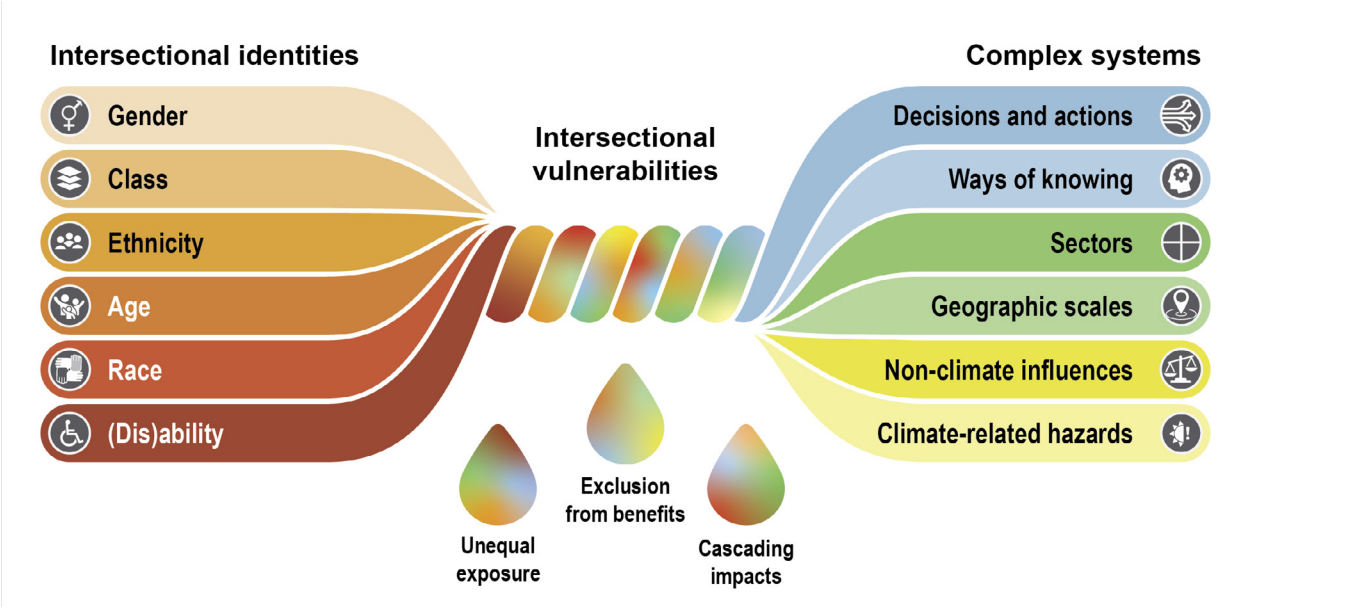
## Box 18.2. Wildfire and COVID-19 Lead to Compounding and Cascading Impacts over Time

Disasters can trigger compounding and cascading effects on displacement. While research has focused on flood-driven displacement in the US,[100,101] other hazards are also intensifying migration pressures (see Figure 20.5). The Camp Fire, which devastated Paradise and surrounding Northern California communities in November 2018, illustrates how climate migration can trigger cascading impacts in places receiving displaced persons (KM 28.4). The Camp Fire killed 85 people, destroyed roughly 19,000 buildings, and displaced more than 50,000 people.[102,103] Many evacuees fled to the nearby city of Chico, which swelled from 93,000 to more than 111,000 people.[104] Chico Police Chief Michael O'Brien said, "You normally would have a decade to prepare for such growth. We had about 10 hours."[102]

In-migration increased traffic by 25%, sewage inflows by 16%, and annual sewage treatment costs by more than $725,000 (in 2022 dollars). It also turned Chico into America's hottest real estate market.[102,105] Telecommuters fleeing the Bay Area during the COVID-19 pandemic further fueled Chico's housing affordability crisis. Even before 2018, only 1.5% of housing starts were affordable to people with very low incomes, and the vacancy rate was less than 1%.[106,107] A political action committee stoked fears around skyrocketing housing prices, new homeless encampments, and crime and drugs to shift the city council from predominantly liberal to conservative. Housing policy began to emphasize evictions and criminalizing unsheltered "vagrants," creating significantly greater risks and impacts for Indigenous Peoples, who are disproportionately represented among the unsheltered.[106]

Since then, climate change, worsening air quality due to subsequent wildfire seasons (Figure 14.3), housing unaffordability, the COVID-19 pandemic, and the shift to teleworking are fueling migration in California from rural to urban areas, from smaller to larger cities, and from coastal cities to more affordable and scenic suburban and rural areas.[108,109,110,111] Across the country, most cities' climate vulnerability and risk assessments focus on future climate impacts to current populations without considering disasters taking place elsewhere that could affect their outlook.[112] Models and assessment tools that account for cascading impacts, especially those conducted at regional scales, can help steer or anticipate the effects of climate-exacerbated migration (e.g., Zoraghein and O'Neill 2020[113]). In addition, national and regional climate-migration and housing-resource models can help inform national and local government infrastructure, land use, and housing decisions.

### Intersectional Vulnerabilities




**Intersecting social and environmental factors privilege some people's ability to respond to climate change.**

**Figure 18.2.** Climate impacts and societal responses exacerbate intersectional vulnerabilities. People's gender, class, ethnicity, age, race, and ability form their intersectional identity (left). Intersectional vulnerabilities emerge when intersectional identities interact with inequities in complex systems, as outlined in Figure 18.1 (right). In the face of climate risks and responses, these intersectional vulnerabilities can result in unequal exposure, exclusion from benefits, and cascading impacts that further impact already-overburdened groups. Societal responses to climate change—including uneven existing resources across municipalities, decisions about where to allocate investments, and noninclusive ways of knowing—can exacerbate existing harms and generate new ones. Adapted with permission from Box TS.4, Figure 1 of Field et al. 2014.[114]

## Key Message 18.3

## Collaborations Among Diverse Knowledge Holders Improve Responses to Complex Climate Challenges

Responding effectively to complex climate challenges benefits from integrated frameworks and modeling approaches that incorporate diverse types of knowledges suited to specific contexts and needs (*high confidence*). Participatory and collaborative approaches and tools bring together diverse knowledge holders and improve the generation and use of actionable knowledge for complex-systems decision-making (*medium confidence*). These collaborative approaches help navigate complex challenges, such as competing perspectives and knowledge uncertainties, thereby improving climate responses (*low confidence*).

Complex-systems responses to climate change require diverse types of knowledge, incorporating different ways of thinking about climate change and complexity, and often arise through participatory and collaborative processes (KMs 12.4, 20.2, 31.3, 31.4).[115,116] While much research focuses on analyses, modeling, or projections specific to individual sectors, regions, or actors, a richer diversity of information is needed to fully understand complexity.[116,117] Decision-making for complex systems benefits from knowledge

of the interdependence of human–natural systems; the venues where decisions are made; the actors participating and impacted by decisions, politics and ideologies; and the values, attitudes, and beliefs of people and institutions (Figure 18.3).[117] Such knowledge stems from diverse disciplines as well as interdisciplinary and transdisciplinary endeavors. Interdisciplinary work integrates knowledge from different disciplines, and transdisciplinary approaches often additionally integrate knowledge from researchers and nonacademic partners such as communities or decision-makers.[118,119,120,121,122] For instance, social science and humanities research that examines the distribution of inequities of climate change has helped to highlight the overlapping and often compounding impacts on overburdened groups and can be used to ensure the inclusion of those communities in climate response decision-making (KM 18.2). Transdisciplinary knowledge that draws from both academic and nonacademic actors can help clarify systemic feedbacks and path dependencies that might go unnoticed if viewed from siloed disciplinary perspectives alone (Figures 18.3, 29.16).[123,124] Overall, complex-systems responses necessitate moving beyond traditional siloed knowledge production processes to integrated approaches that include diverse types of knowledge and actors.[125,126,127]

The diverse types of actionable knowledge needed for responding to complex climate risks include data and modeling, decision support tools, case studies, art, and lived experiences (KMs 4.3, 13.2, 17.1; Box 19.1). Different types of knowledge can be critical depending on the context and needs. For instance, qualitative forms of knowledge, such as oral histories or ethnographies, provide rich, place-specific understandings of how complex systems function and how climate-related experiences influence behavior.[128] Narratives and crowdsourced data of extreme events, including how people cope with them, have improved the integration of climate knowledge into social and cultural life.[129] Stories have advanced climate and energy solutions by allowing exploration of the intersection of nature, humanity, and technology.[130]

Integrated frameworks that bring together different knowledge types across various sectoral and regional contexts are essential for holistic analyses of complex systems. For example, recent developments in coupled human–natural systems modeling have not only examined cascading impacts across sectors and scales but have also incorporated the feedback relationships from social and political systems back into the models.[131] The Water Utility Climate Alliance has used a "chain of models" approach to link global climate models (GCMs) to hydrological models and then water utility decision-making tools.[132] Connections between GCMs and urban tree canopy models have supported analysis of heat management strategies across multiple dimensions, including air quality, irrigation demand, and greenhouse gas emissions.[133,134,135] Food–Energy–Water (FEW) systems studies have developed frameworks[126,136] to better understand regional to global dynamics within cross-sectoral FEW systems.[131,137]

These advanced integrated frameworks draw on knowledge that stems not just from academics and researchers, but also from a wide range of experts, including practitioners, decision-makers, and local and Indigenous Peoples.[116,127,138,139,140] There are increasing examples of community and citizen scientists monitoring specific environmental indicators at temporal and spatial scales otherwise infeasible (see Table 12.2).[141,142,143,144] The long-term environmental knowledge and socioecological memory held by Indigenous Peoples has helped to detect, understand, and predict complex changes in climate systems.[138,145] Further, land management approaches based on Indigenous Knowledge have long emphasized flexibility and diversity of resources and serve as successful examples of resilient practices under complex environmental changes (e.g., Box 27.3).[138]

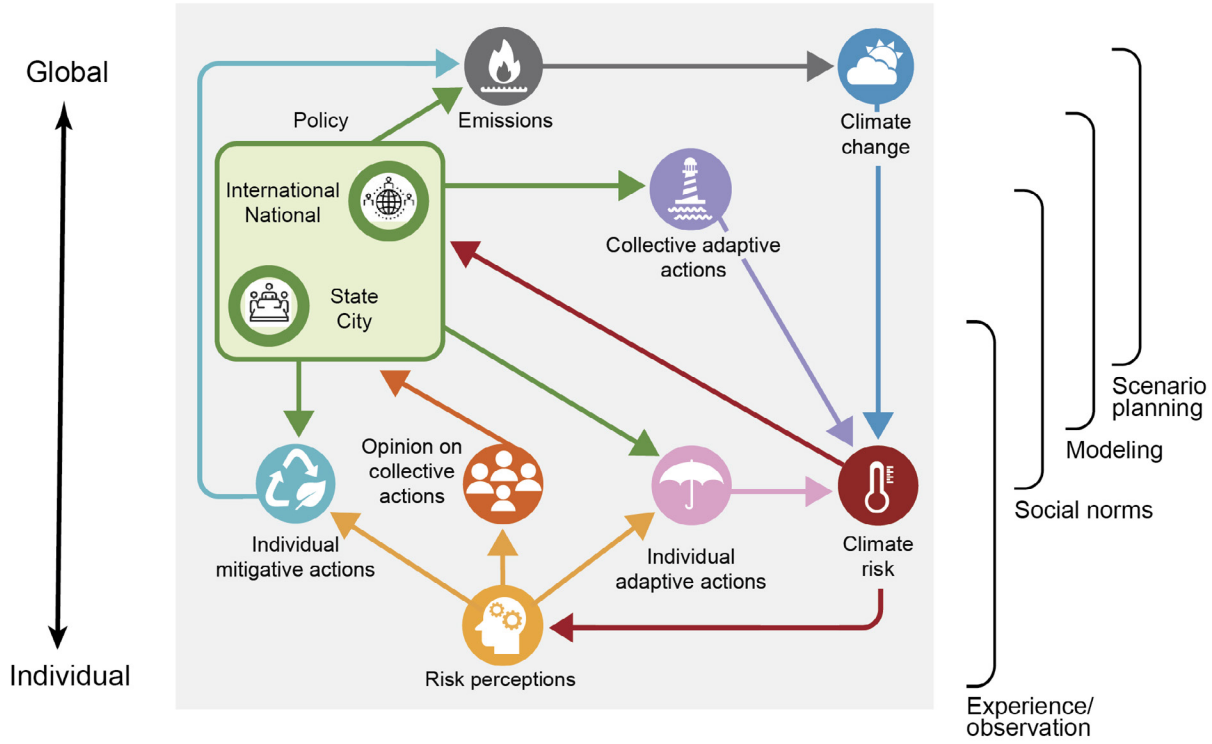
Connecting different knowledge holders and knowledges requires a different type of scientific practice that is more collaborative, participatory, or community-engaged.[116,146,147,148,149] Approaches such as coproduction, which bring together diverse knowledge holders with potential knowledge users, have proven to be successful in developing actionable knowledge for complex systems (Box 18.3; see Key Message 20.2 for more on engaging diverse stakeholders).[150,151,152] Such approaches allow for iteration and deliberation about multiple worldviews and have been effective in improving credibility, relevance, and trust

in knowledge.[115,139,153,154] They also enable better understanding and management of knowledge uncertainties.[154,155,156] For example, participatory modeling of complex socioecological systems has included experience-based practitioner knowledge to improve identification of system boundaries, elicit realistic management alternatives, and increase the decision-relevance of outputs.[21,132,140,157] The county of Los Angeles has used participatory modeling to identify cascading impacts across infrastructural systems, their downstream effects for residents, and key intervention points.[158] Collaborative decision-making under deep uncertainty (DMDU) approaches, such as flexible adaptation pathways, scenario planning, and decision scaling, seek to develop robust climate responses for multiple potential futures rather than planning for a single best-estimate future, and they have also been positively received by decision-makers (see Figure 18.4).[159,160,161] The US National Park Service has used collaborative scenario planning, bringing together natural and cultural resource managers and subject-matter experts, to negotiate social and scientific uncertainties associated with climate change and inform the setting of conservation and resource stewardship goals.[162,163,164,165]

Effectively implementing and sustaining such collaborative processes requires specialized boundary organizations and climate services agencies (Box 18.3).[166,167,168] These boundary agencies facilitate, translate, and mediate engagements between scientists and different actor groups. NOAA's Climate Adaptation Partnerships, USGS's Climate Adaptation Science Centers, USDA's Climate Hubs, and university agricultural extension services have emerged as leading boundary agencies for the production and use of climate information through trust- and partnership-building with various knowledge-holder and user groups.[169,170]

Evaluation of effectiveness and equity is an important aspect of efforts to use climate-relevant knowledge in complex-systems decision-making. While there is increasing evidence that many collaborative approaches (such as coproduction, collaborative scenario planning, and DMDU tools) have been effective in improving the production and use of complex-systems knowledge in decision-making (Box 18.3), there has been limited examination of the long-term outcomes and equity of these processes and tools.[151,152,171] Additionally, the relative advantages and disadvantages of when and where different types of knowledges are most useful is also not well understood.[119,172] Overall, despite preliminary successes, understanding of the transferability, impact, and equity of different collaboratively generated knowledge and tools is still emerging.

## Interacting Climate Responses and Knowledges Across Scales




**Climate responses, ranging from the individual to global scale, interact with and draw from diverse knowledges.**

**Figure 18.3.** Activities of government at multiple scales (green) affect climate risk (red) via multiple pathways, by decreasing or increasing greenhouse gas emissions (gray) and supporting adaptive (or maladaptive) actions (pink, purple). Moreover, government actions are influenced by the opinion and interests of residents, businesses, and other organizations (orange), and they in turn shape the actions of households and businesses (pink, blue). Interacting actors are nested within multiple spatial scales (left) and also rely on different knowledge sources for decision-making (right). Adapted from Moore et al. 2022.[88]

## Box 18.3. Different Forms of Knowledge and Collaboration Across Groups Support Local Adaptation

Governments, businesses, community organizations, and residents in coastal cities have been early implementers of collaborative approaches to create actionable knowledge for complex climate responses (KM 22.1; see also Box 9.1). The Little River Adaptation Action Area in Miami-Dade County, Florida, is one such example of a new flexible planning tool.[173] This area is exposed to flooding worsened by sea level rise, and the challenges can be particularly stark. For example, when high tides and rainfall happen at the same time, septic tanks fail, leading sewage to back up into homes and spill into and contaminate waterways. As one resident described it, "I could live with a little bit of flooding if I knew the water wasn't full of sewage."[173] Systemic drivers of disparities across neighborhoods go back decades, and financial hardship means that households often struggle to reduce risks from flooding, as well as from chronic humid heat in the home.[174] Starting out in 2020, the Little River Adaptation Action Area has three main goals: 1) to use data to inform capital projects reducing climate risks (see also KM 31.5), 2) to support collaborative approaches in which community members' knowledge and experience guide climate solutions (see also KM 31.3), and 3) to break down silos and coordinate responses across governments, households, and the private sector. Implementation of this flexible adaptation tool has been led by resilience staff in the region, including importantly municipal chief resilience officers. Supported by research–practice partnerships such as the Resilient305 Collaborative, the county has enabled community-based implementation of multiple regional climate strategies.[173,175,176,177,178]

The Little River Adaptation Action Area has thereby been able to test out collaborative approaches and improve responses to complex climate challenges. First, the planning effort has been guided by overarching principles such as making residents safer through equitable engagement, fair policies, and direct investments; working with nature; and supporting flexible, integrated climate responses.[173,175,176] These guiding principles create clear signposts for designing and updating the collaborative planning process. Second, community workshops and research–practice networks have supported the use of physical and socioeconomic information and diverse knowledges in exploring locally preferred response strategies with support from state and federal partners, such as septic-to-sewer conversion, expansion of green spaces, and improvement of housing.[174,178,179] Granular, transparent data are being used to understand the distribution of climate and policy impacts such as flood and heat exposure across communities, as well as to understand building, household, and neighborhood characteristics that shape impacts on families. Third, evaluation has been embedded into planning efforts, such as by monitoring investments made and how residents perceive them.[180] These evaluation efforts require commitment and rigor, and they are necessary to understand how effective climate responses are for both climate goals and broader priorities, to identify unexpected benefits, and to support course corrections where needed. Fourth, approaches are expanding to address deeper uncertainties, such as the implications of large amounts of sea level rise and pathways that could help ensure longer-term flexibility where it may be needed.[181]

## Key Message 18.4

## New Governance Approaches Are Emerging, but Gaps in Practice and Evidence Persist

Climate change presents challenges for managing risks and responses across different levels of government, the private sector, and civil society. Current governance entities and their existing jurisdictional authorities are often unable to resolve conflicts posed by the wide-ranging and unprecedented interactions and complexities of climate risks and more localized compounding stressors (*high confidence*). Local and regional governments have experimented with alternative institutional arrangements, funding mechanisms, and decision coordination (*medium confidence*). Thus far, however, there is only preliminary evidence of their effectiveness (*low confidence*). These pilots and other innovations developed for climate mitigation and adaptation may well present opportunities for replication and broader successes in other locations and different local contexts (*medium confidence*).

Climate responses and management practices are expanding to address complexity in coevolving human–natural systems. The need for science-informed, inclusive decision-making around complex climate risks is immense. The form and quality of governance of individual and interacting systems are shaped by government agencies, civil-sector actors, and private-sector entities.[182] The actors and their roles vary across jurisdictions and are dependent on constitutional authorities, modes of control (e.g., proprietary, regulatory, budgetary), geographic territories, climate-related functions, technical capacities, budgets, access to financial and intellectual resources, and institutional or political power. The current state of these factors depends on institutional legacies and their momentum or inertia in response to changing climate conditions.[183]

There are inherent challenges in governing complex systems in response to climate change (KM 31.3). Relevant jurisdictions tend to be highly defined and siloed despite overlapping social or environmental system interactions.[184] Structural inequities established in past governance institutions are often inextricable from current decision-making processes (KM 20.1). Market failures are sometimes ignored (e.g., disclosure of a property's climate risks) or exacerbated by public policy (e.g., securitizing mortgages for risky properties, paying out insurance claims for repeat losses, or decreasing housing affordability as a result of mitigation efforts). Access to financial and intellectual resources has historically been weak at the local level and highly variable across geographies and urban to rural gradients.[185] Governance of complex systems requires flexibility beyond the formal governance of any one system.[186] Alternative processes for decision-making have been proposed or are in preliminary levels of implementation. These include an increased and explicit reliance on available scientific, engineering, and social-science evidence to inform policy. Iterative, participatory planning and deliberation inclusive of all residents or stakeholders are also possible. Similarly, transparency and accountability in public information and deliberations are increasingly important. Improved coordination strategies between governing entities—adjusting to evolving conditions and improving information—include decentralization and de-siloing in the public sector across agencies or jurisdictions, effectively reorganizing government. Governing entities are also looking at making longer-term commitments in public works and social programming and in longer-term visioning scenarios than their current budgetary and planning terms have traditionally prescribed (KM 12.4). Finally, governing institutions increasingly recognize the distribution of risks, path dependencies, and costs and burdens across communities.[18,187]

The state of evidence on effective governance approaches varies for each characteristic of complex-systems management:

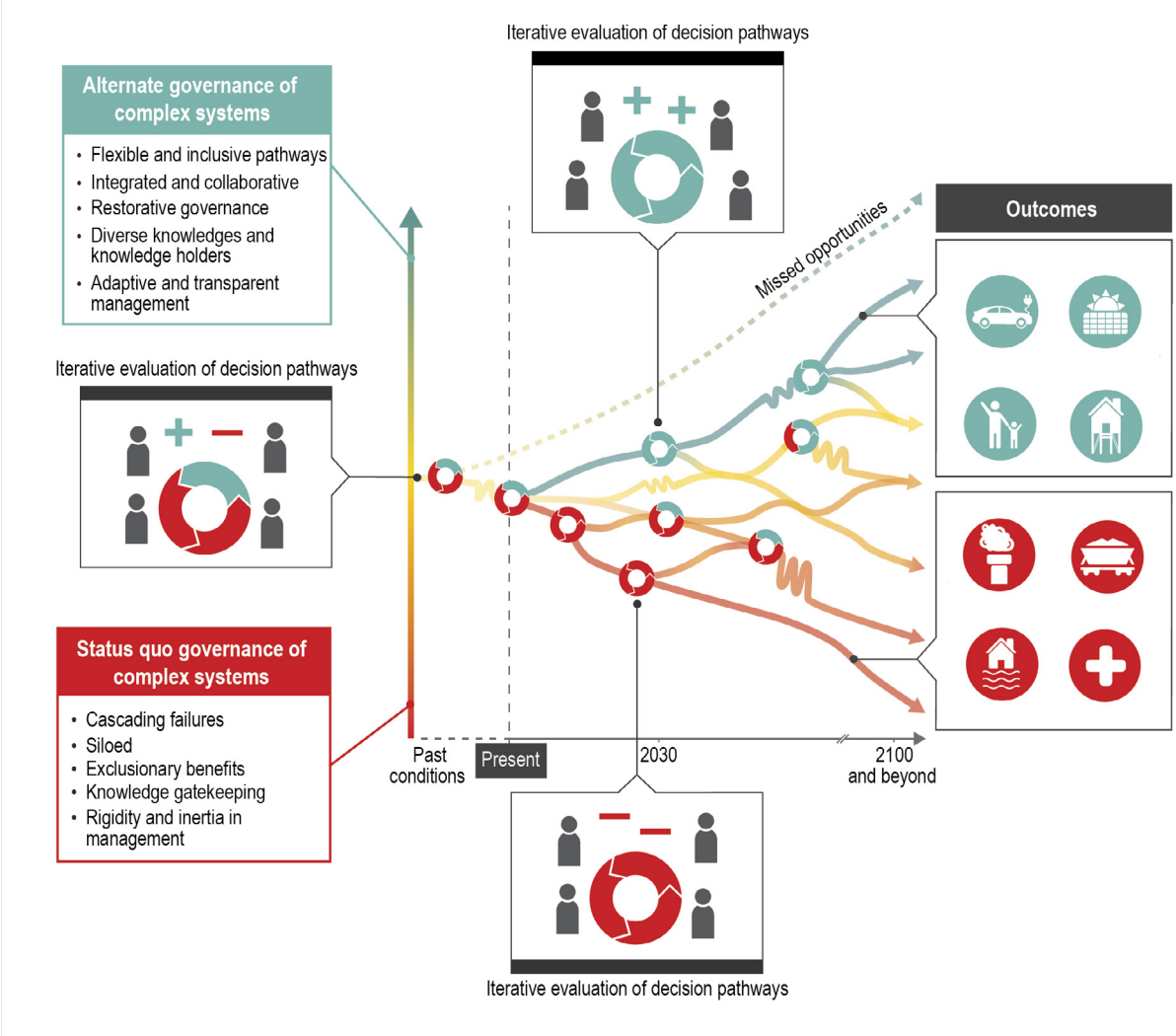
- Complex systems are often characterized by *deep uncertainty*—the presence of systemic structural uncertainties or unknowns without objective probabilities. Climate risks and possible scenarios exacerbate this uncertainty (KM 18.1). Stakeholders such as private-sector interests, public-sector officials, and civil-sector representatives may disagree about the likelihood of future scenarios or consequences of decisions. Effective governance approaches include transparency in system frameworks, integration of contingencies and redundancies, and flexible planning and operations to avoid decisions that are costly or impossible to reverse (Figure 18.4).[188,189,190,191] Actors are already revisiting their crisis management plans to avoid worst-case outcomes and reduce short-term losses.
- Wide-ranging actors within complex systems may have *multiple, often competing objectives* regarding climate actions. In response, effective governance approaches include establishing consistent criteria to evaluate alternative actions, sometimes using consensus-based principles. Inclusive governance, stakeholder consultation, and explicit consideration of multiple criteria are other strategies for addressing cross-system conflicts. However, interactions among actors across overlapping governance structures and systems, combined with strategic behavior for individual decisions, can complicate these processes.[192,193,194,195,196]
- Complex systems are often characterized by *broadly distributed knowledge and power*—with diverse actors controlling knowledge about different parts of the system. Approaches in these polycentric governance systems include processes for data sharing, decision coordination and deliberation, and de-siloing of decision-making in related areas.[117,197,198,199,200,201,202,203,204,205,206,207,208,209,210,211,212] Mechanisms such as market-based approaches can sometimes allow for interaction of diverse actors via price signals, reducing the need for direct, centralized regulations, although these efforts may not account for inequitable financial access and outcomes across stakeholders, particularly overburdened communities.[213,214]
- Governance of complex systems tends to be *geographically and functionally nested*—controlled by multiple jurisdictions such as municipal, state, and federal authorities (Figure 31.4). Coordination across actors in different jurisdictions, together with improved clarity and boundary definitions, can therefore be valuable (Figure 18.3). The primary tools of nested governance structures—that is, regulation, statute, program rules, and coordinated budget transfers from multiple sources—can be negotiated through coordination rather than preemption.[202,215,216,217,218,219,220,221,222,223,224]
- Finally, *feedbacks and path dependencies* are common in complex systems. Choices at one point in time, such as the capacity and siting of physical infrastructure projects, can either expand or limit options later on (Figure 18.4). As a result, the full effects of management actions can be difficult to anticipate, particularly in the longer run. Path dependencies and policy feedbacks can lead to immediate commitments that restrict later change. Effective governance strategies include adaptive management approaches that repeatedly monitor, evaluate, and amend actions, although such governance strategies are not well developed.[225,226,227,228,229,230,231,232,233,234,235]

Overall, there is only preliminary evidence of the effects of alternative governance structures on climate mitigation and adaptation actions or their outcomes. Existing governance structures largely predate contemporary public climate responses and extend histories of US federalism, home rule, privatization, and ad hoc regional collaborations or special districts created in response to temporal needs or crises. These structures have generally not been reconfigured in the face of complex climate challenges, with some exceptions (KM 31.3). The governance structure between the Federal Government and state governments across and between most systems is constitutionally defined. The resulting flows of resources and other forms of assistance are therefore statutorily defined by program authorizations and appropriations. Existing

governance entities such as state government agencies have attempted broad internal coordination among sub-state governments, although adjustments have met with varied success and contested leadership.[236]

There are more examples of alternative governance structures between and within subnational governments. Examples of the former include the cross-state Regional Greenhouse Gas Initiative for climate mitigation actions or the cross-county Southeast Florida Regional Climate Change Compact (Box 18.3) for climate adaptation; these efforts attempt to manage multiple systems across different jurisdictions.[237,238] Other regional coordinating entities have been created across states, counties within states, or cities within counties, including those affiliated with the Alliance of Regional Collaboratives for Climate Adaptation. But these efforts are typically preempted or bounded by the constitutional authorities allowed by the superseding level of government (for example, a state over counties). There is preliminary evidence about the effectiveness of individual climate professionals (e.g., chief resilience officers and related boundary-spanners).[203,239] However, the long-term outcomes from these efforts have not been conclusively measured.[240]

## Governance of Complex Systems




**Governing complex systems involves pathways of decision-making across time.**

**Figure 18.4.** Adaptively managing complex systems involves a series of choices and actions through time. There are path dependencies shaped by the past and present, opportunities for maintaining flexibility under deep uncertainties, and needs for iterative learning through time. Governance of complex systems is more effective when it is flexible, inclusive, integrated, collaborative, and adaptive. At each decision point in time (circles with arrows), diverse decision-makers evaluate possible solutions available at that time and choose a path forward (people in gray considering benefits and trade-offs of different possible pathways). Given these responses, alternate pathways (red, orange, yellow, and green) may remain possible for the future or become closed off. At each decision point, an important consideration is how actions taken may expand or contract the options available in the future. Adapted with permission from Figure SPM.6 in IPCC 2023.[241]

# Traceable Accounts

## *Process Description*

The scope of this chapter was first developed by considering 1) the corresponding chapter in the Fourth National Climate Assessment (NCA4) as a starting point; 2) new emphases on topics relevant to complex systems, intersectoral interactions, and multiple stressors across NCA5; and 3) evolving areas of research and practice. The chapter lead identified important areas of expertise for the author team, including complex-systems methods, engagement methods, and topical expertise (e.g., energy–water–land, coastal, urban). Potential authors were identified from the nominations database, literature searches by the chapter lead and coordinating lead author, and the authors of the NCA4 chapter.

The First Order Draft, Second Order Draft (2OD), Third Order Draft (3OD), and Fourth Order Draft (4OD) were developed from the Zero Order Draft (ZOD) narrative outline through a multistage process. First, feedback on the framework and topics of the chapter was solicited via a public engagement workshop. Discussions focused on the NCA5 chapter framework for complexity, lived experiences, and the management of complex interactions. Second, chapter authors discussed the outline, and a lead author, along with accompanying contributors, was identified for each Key Message, figure, and box. Third, drafting proceeded through iterative processes of full-team and subgroup conversations on the scope and approach for each chapter element, literature reviews, and preparation of text and graphics, as well as identifying emerging assessment findings, areas of overlap across chapter sections, and potential directions for refinement in subsequent drafting stages. Fourth, cross-chapter discussions and the ZOD public review comments were used in the revision of the 2OD. These themes were further prioritized as the chapter was revised in the development of 3OD text and figures, also incorporating the review comments on the 2OD. The 4OD was then developed on the basis of public review and NASEM (National Academies of Sciences, Engineering, and Medicine) comments, with monitoring by the chapter review editor.

## Key Message 18.1

## Human–Nature Interconnections Create Unexpected Climate Risks and Opportunities

### Description of Evidence Base

Key Message 18.1 material draws heavily from the recent assessment conducted in development of the Multisector Dynamics (MSD) vision report,[3] which was an in-depth assessment by a diverse research community directly building from NCA4, as well as recent literature outside the scope of that report. In addition to citing the report itself, Key Message 18.1 directly cites underlying literature from the MSD vision report and other fields such as socio-ecological-technical systems, sociohydrology, complex systems, exploratory modeling, and decision-making under deep uncertainty.[5,12,13,14,15,16,17,18,25,54,56,242] Given this foundation, the Key Message draws from an expansive evidence base, for which agreement in the literature pertains both to areas of agreement across studies and to deep uncertainties that remain.

Figure 18.1 is a combination of new and existing work. The underlying source was a conceptual diagram of complexity in urban systems and the lenses through which it can be organized and understood. Here, the figure has been adapted for complex systems as a whole, pursued through an actor-oriented lens and reflecting the authors' review of figures that explain different aspects of complexity in socioecological systems or coupled human–natural systems under a changing climate.[5,29,243,244,245,246,247,248,249] The MSD vision report executive summary Figure 1 was also a source of inspiration, yet the figure included in this

Assessment centers actors and their capacities to respond. This adjustment reflects increasing recognition of the role of people in complex systems and associated climate risks and responses.

### Major Uncertainties and Research Gaps

Major uncertainties are explicitly acknowledged in the discussion of deep uncertainties inherent to complex systems. Based on the available literature, we provide assessment of emerging approaches relevant to complex systems under such uncertainties. There are deep uncertainties in predicting complex interconnections among human and natural systems over long time periods, which are particularly exacerbated by a lack of human systems research that focuses on the interactions between human and natural systems.[12,14,22] Exploratory systems modeling[52,53,54] is developing approaches to address these deep uncertainties.

### Description of Confidence and Likelihood

Given the robust evidence underpinning this foundational section of the chapter, along with high agreement about that evidence (see especially the foundational assessment by Reed et al. 2022b[3]) Key Message 18.1 is assessed with *high confidence* overall. The first confidence-assigned statement in the Key Message describes the increasing vulnerability of interconnected human–natural systems to risks from climate change. Given the high degree of agreement among voluminous sources of evidence,[1,3,5,12,14,15,16,20,25,26,28,29,30,35,242,248,250], we assign *high confidence* to this statement. The second statement describes how these vulnerabilities depend on human responses and other compounding stressors. Given the high degree of agreement among many sources of evidence (see above), we assign *high confidence* to this statement. The final statement describes the diverse and sometimes competing objectives that decision-makers will need to navigate in managing climate risks. Given the high degree of agreement among ample sources of evidence (see above), we assign *high confidence* to this statement.

## Key Message 18.2

## Complex Climate Impacts and Responses Further Burden Frontline Communities

### Description of Evidence Base

Evidence of the intersectional impacts of natural hazards, decarbonization efforts, and climate adaptation is well documented. Quantitative assessments of program outcomes and post-disaster outcomes, with a large number of data points, consistently show that more rural or smaller municipalities are less able to attract resources for adaptation (e.g., Mach et al. 2019[83]). Numerous case studies and spatial and quantitative assessments provide evidence of the displacement tendencies of climate-exacerbated disasters and climate mitigation and resilience initiatives.[73,85,109,251,252,253] In-depth qualitative research and longitudinal studies of overburdened communities have studied how cyclical disasters erode community response capacity[254,255,256] and trigger cascading infrastructure and housing effects in cities receiving groups migrating from or displaced by climate-related events and trends.[103] Research on the climate transition from fossil fuel economies shows that these efforts intersect with social, cultural, and political challenges to create intersectional vulnerabilities and complexities.[257,258]

### Major Uncertainties and Research Gaps

Just as important as what we know about distributive impacts in complex systems is what we do not know or measure. Most research assessing complex systems is highly technocratic, focusing on specific events, discrete risks, and the impacts of cascading infrastructure systems, demographic change, and natural resource systems. However, complexity studies do not tend to encompass the large body of social and

humanities research—increasingly focusing on climate change—related to cultural, psychological, and effective responses to shocks; racial, gender-based, and equity-oriented studies of vulnerabilities, risks, and societal responses; or the roles of political ideology and violent conflict (e.g., Palmer and Smith 2014;[89] Beckage et al. 2020;[87] Moore et al. 2022;[88] Reed et al. 2022,[242] 2022;[3] Rising et al. 2022[90]). These issues can help explain political decision-making, protests, and post-disaster conflicts and are important for understanding interactions across social and physical systems in the near and long term. There is a resulting lack of tools and communities of practice to integrate disciplinary divides in support of complex-systems research.

Limited knowledge about climate-exacerbated migration and how receiving cities are responding results in uncertainties about how climate migration differs from other forms of migration, what migration means for overall vulnerability trends, and how it will impact other interlinked physical and natural systems. Information on urban–rural linkages is limited, especially in forms that can support complex-systems modeling. Trade-offs between mitigation efforts and adaptation strategies with competing impacts on individuals' well-being are also understudied.

### Description of Confidence and Likelihood

There is *high confidence* in each statement of Key Message 18.2. First, there is high agreement in the literature that climate change disproportionately impacts already-overburdened groups (statement 1), as recently assessed in the comprehensive Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group II.[69] Second, multiple studies with high agreement across them have documented the lack of social and political dynamics in complex-systems models and limitations resulting from sectoral, regional and jurisdictional, and disciplinary silos of vulnerability and risk assessments (statement 2).[3,86,87,88,89,90,242] Some complex-systems analyses have made first steps in incorporating social and political dynamics (e.g., Moore et al. 2022[88]), but these are emerging efforts, and statement 2 is therefore made with *high confidence*. Third, data about how complex systems affect frontline communities is lacking for hard-to-reach populations, and this can lead to disproportionate climate impacts (statement 3).[97,99] This statement is made with *high confidence* given the large evidence basis on inequalities in data availability and quality across communities and the focus of the literature on data-rich places (e.g., Friel et al. 2011;[98] Pörtner et al. 2022;[69] Reed et al. 2022[3]).

## Key Message 18.3

## Collaborations Among Diverse Knowledge Holders Improve Responses to Complex Climate Challenges

### Description of Evidence Base

Key Message 18.3 and corresponding text draw from a review of various types of literature on knowledge for complex systems, several author team meetings and deliberations over written documents, and takeaways from the public engagement workshop. The write-up was also coordinated with authors of other Key Messages, especially Key Messages 18.2 and 18.4. Literature reviewed for this Key Message spanned several topical areas. The authors reviewed literature describing integrated frameworks and modeling for complex systems,[3,123,126,127,131,136] as well as characteristics of actionable or usable knowledge.[115,116,120,153,154] Authors also focused on literature showcasing the role of qualitative knowledge such as narratives in managing complex systems.[128,129,130] In terms of knowledge production processes, the team reviewed the latest papers on co-production of knowledge and collaborative research approaches, as well as on interdisciplinary and transdisciplinary research.[115,124,147,259] The authors also reviewed literature and case studies on Indigenous and Traditional Knowledges and their role in complex systems, as well as the role of citizen science.[141,142,143,144]

Studies on participatory modeling,[21,140,156,157] as well as collaborative decision-support tools for complex systems such as decision-making under deep uncertainty and scenario planning, were also reviewed. Finally, research on climate services and boundary agencies was also reviewed.

Box 18.3 centers on complex coastal governance, drawing from evaluations of climate responses in Metropolitan regions including the San Francisco Bay area, Los Angeles County, Southeast Florida, and metropolitan New York; a specific case example of the Little River Adaptation Action Area is discussed here. Multiple recent studies have examined the science–policy–practice processes and partnerships, along with the evolving governance systems, inherent to complex coastal climate responses (e.g., Treuer et al. 2017;[260] Kim 2019;[261] Solecki et al. 2021;[262] Tedesco et al. 2021;[179] Troxler et al. 2021;[178] Lubell and Robbins 2022[263]). Direct references are provided to relevant regional strategies and decision support forums (e.g., Miami-Dade County 2021;[176] Miami-Dade County 2021;[175] SFWMD 2021[177]).

### Major Uncertainties and Research Gaps

Despite the promise and potential of collaborative knowledge production processes and collaborative decision tools, long-term monitoring and evaluation of these processes and tools are largely lacking; hence, the long-term impact and effectiveness of such collaboratively generated knowledge in responding to complex climate risks in complex systems are not well understood.[147,151,172,264] In addition, the impact of collaboratively generated actionable knowledge on long-term management of complex climate-impacted systems, particularly as it relates to procedural or distributive justice in outcomes, is not well understood.[265]

### Description of Confidence and Likelihood

There is high agreement in the literature, from both theoretical[120,124,127] and empirical studies,[117,123,131,263] that effective complex systems responses benefit from integrated frameworks that bring together diverse and context-specific knowledge. Therefore, there is *high confidence* in the first statement in this Key Message. A growing number of studies provide evidence that participatory and collaborative approaches that bring together diverse actors have improved the actionability of knowledge for managing complex systems,[150,151,152] but more evidence is needed on the extent to which this actionable knowledge has actually been used in complex-systems decision-making.[266,267,268] Hence, there is *medium confidence* in the second statement. Although the theoretical literature suggests that collaborative approaches help to navigate competing perspectives of different actors and knowledge uncertainties,[43,117,119] there are very few studies that have evaluated the extent to which these approaches have successfully led to improved climate responses in the long term.[171,267,269,270] Hence, there is *low confidence* in the third statement.

## Key Message 18.4

## New Governance Approaches Are Emerging, but Gaps in Practice and Evidence Persist

### Description of Evidence Base

The subgroup of authors for Key Message 18.4 pulled from a multidisciplinary set of research products at the intersection of governance, regional planning, systems theory, and jurisdictional authority in relation to both climate mitigation and adaptation planning, actions, outputs, and outcomes.[202] The subgroup identified key peer-reviewed research products based on the themes categorized by subgroup members' expertise, as well as the themes that surfaced in the public engagement workshop; essentially, the identification of sources was expansive, but the themes from which the sources were identified and classified were necessarily limited. Further, the subgroup sought to identify documentation of alternative governance successes and

failures in relation to climate mitigation and adaptation in order to expand the pool of sources to other disciplines that may not explicitly use governance terms.[191] For each of the themes identified, there is a vast literature from which to pull findings. Identifying these was a straightforward process, and there was minimal disagreement on either the themes or the sources.

In slight contrast, there was significant discussion regarding the level of confidence around the synthesis of sources' findings, given their range of empirical inquiry and methodological rigor. The vast majority of evidentiary sources rely on either singular governance case studies (or, less often, a few cases) or theoretical exploration in either qualitative or quantitative ways.[195,199] Fewer studies include sample sizes of governance cases that are powerful enough—or that employ comparison groups of any design—to produce conclusive and generalizable findings.[203,221] Consequently, assessments of uncertainties and confidence are based largely on the variable rigor of these sources.

## Major Uncertainties and Research Gaps

Governance, by definition, varies by geographic, social, and political landscapes, among many contextual factors. The first factor—geography—poses a particular challenge for the development of conclusive evidence of governance actions and effects.[188] Essentially, each place has a unique governance framework.[117] Although rigorous qualitative and quantitative studies have been conducted regarding governance interventions and their outcomes in specific places, the sample sizes of individual monographs and consistent application of terms across them have consequently produced only preliminary evidence to date. As with urban studies and political geography, there are few multisite studies of complex-systems governance at any level of quasi-experimental rigor, or even basic outcome evaluations, that allow for replicable responses to the fundamental question posed in the public engagement workshop: What is "good" climate governance?

## Description of Confidence and Likelihood

This fundamental methodological challenge, then, prohibits an assessment of *high confidence* for all complex-systems governance themes—with the sole exception of their current inability to produce consistently positive outcomes. Further study with larger sample sizes and consistent terms of governance frameworks—including their inputs, activities, outputs, and outcomes—is necessary to assess higher levels of confidence. Statements in the Key Message regarding evaluation/learning, effectiveness, and replicability are therefore made with *low* and *medium confidence*. The quantity of evidence around climate governance implementation and outcomes is too small to conclude that their findings are externally valid and replicable.[203] Policy and governance literature for other subject domains beyond climate mitigation and adaptation for which there has been more extensive study, however, suggests that pilot governance efforts' success may not be insignificant, implying a higher confidence that the implementation of current climate pilots may also yield positive outcomes.[200,224]

# References


1. Helbing, D., 2013: Globally networked risks and how to respond. *Nature*, **497** (7447), 51–59. https://doi.org/10.1038/nature12047

2. Schweikert, A.E. and M.R. Deinert, 2021: Vulnerability and resilience of power systems infrastructure to natural hazards and climate change. *WIREs Climate Change*, **12** (5), e724. https://doi.org/10.1002/wcc.724

3. Reed, P.M., A. Hadjimichael, R.H. Moss, E. Monier, S. Alba, C. Brelsford, C. Burleyson, S. Cohen, A. Dyreson, D. Gold, R. Gupta, K. Keller, M. Konar, J. Macknick, J. Morris, V. Srikrishnan, N. Voisin, and J. Yoon, 2022: MultiSector Dynamics: Scientific Challenges and a Research Vision for 2030. U.S. Department of Energy, Office of Science. https://doi.org/10.5281/zenodo.6144309

4. Rinaldi, S.M., J.P. Peerenboom, and T.K. Kelly, 2001: Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine*, **21** (6), 11–25. https://doi.org/10.1109/37.969131

5. Simpson, N.P., K.J. Mach, A. Constable, J. Hess, R. Hogarth, M. Howden, J. Lawrence, R.J. Lempert, V. Muccione, B. Mackey, M.G. New, B. O'Neill, F.E. Otto, H.-O. Pörtner, A. Reisinger, D. Roberts, D.N. Schmidt, S. Seneviratne, and C.H. Trisos, 2021: A framework for complex climate change risk assessment. *One Earth*, **4** (4), 489–501. https://doi.org/10.1016/j.oneear.2021.03.005

6. Vespignani, A., 2010: The fragility of interdependency. *Nature*, **464** (7291), 984–985. https://doi.org/10.1038/464984a

7. Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105** (6), 1786–1793. https://doi.org/10.1073/pnas.0705414105

8. Glazer, Y.R., D.M. Tremaine, J.L. Banner, M. Cook, R.E. Mace, J. Nielsen-Gammon, E. Grubert, K. Kramer, A.M.K. Stoner, B.M. Wyatt, A. Mayer, T. Beach, R. Correll, and M.E. Webber, 2021: Winter storm Uri: A test of Texas' water infrastructure and water resource resilience to extreme winter weather events. *Journal of Extreme Events*, **08** (04), 2150022. https://doi.org/10.1142/s2345737621500226

9. Cohen, J., L. Agel, M. Barlow, C.I. Garfinkel, and I. White, 2021: Linking Arctic variability and change with extreme winter weather in the United States. *Science*, **373** (6559), 1116–1121. https://doi.org/10.1126/science.abi9167

10. Overpeck, J.T. and B. Udall, 2020: Climate change and the aridification of North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (22), 11856–11858. https://doi.org/10.1073/pnas.2006323117

11. Wieder, W.R., D. Kennedy, F. Lehner, K.N. Musselman, K.B. Rodgers, N. Rosenbloom, I.R. Simpson, and R. Yamaguchi, 2022: Pervasive alterations to snow-dominated ecosystem functions under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (30), e2202393119. https://doi.org/10.1073/pnas.2202393119

12. Bai, X., R.J. Dawson, D. Ürge-Vorsatz, G.C. Delgado, A.S. Barau, S. Dhakal, D. Dodman, L. Leonardsen, V. Masson-Delmotte, D.C. Roberts, and S. Schultz, 2018: Six research priorities for cities and climate change. *Nature*, **555**, 23–25. https://doi.org/10.1038/d41586-018-02409-z

13. Berrang-Ford, L., A.R. Siders, A. Lesnikowski, A.P. Fischer, M.W. Callaghan, et al., 2021: A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, **11** (11), 989–1000. https://doi.org/10.1038/s41558-021-01170-y

14. Brelsford, C., M. Dumas, E. Schlager, B.J. Dermody, M. Aiuvalasit, M.R. Allen-Dumas, J. Beecher, U. Bhatia, P. D'Odorico, M. Garcia, P. Gober, D. Groenfeldt, S. Lansing, K. Madani, L.E. Méndez-Barrientos, E. Mondino, M.F. Müller, F.C. O'Donnell, P.M. Owuor, J. Rising, M.R. Sanderson, F.A.A. Souza, and S.C. Zipper, 2020: Developing a sustainability science approach for water systems. *Ecology and Society*, **25** (2), 23. https://doi.org/10.5751/es-11515-250223

15. Di Baldassarre, G., N. Wanders, A. AghaKouchak, L. Kuil, S. Rangecroft, T.I.E. Veldkamp, M. Garcia, P.R. van Oel, K. Breinl, and A.F. Van Loon, 2018: Water shortages worsened by reservoir effects. *Nature Sustainability*, **1** (11), 617–622. https://doi.org/10.1038/s41893-018-0159-0

16. Mora, C., D. Spirandelli, E.C. Franklin, J. Lynham, M.B. Kantar, W. Miles, C.Z. Smith, K. Freel, J. Moy, L.V. Louis, E.W. Barba, K. Bettinger, A.G. Frazier, J.F. Colburn Ix, N. Hanasaki, E. Hawkins, Y. Hirabayashi, W. Knorr, C.M. Little, K. Emanuel, J. Sheffield, J.A. Patz, and C.L. Hunter, 2018: Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nature Climate Change*, **8** (12), 1062–1071. https://doi.org/10.1038/s41558-018-0315-6

17. Müller, M.F. and M.C. Levy, 2019: Complementary vantage points: Integrating hydrology and economics for Sociohydrologic knowledge generation. *Water Resources Research*, **55** (4), 2549–2571. https://doi.org/10.1029/2019wr024786

18. Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372** (6549), 8054. https://doi.org/10.1126/science.abc8054

19. Andersen, A.D., M. Steen, T. Mäkitie, J. Hanson, T.M. Thune, and B. Soppe, 2020: The role of inter-sectoral dynamics in sustainability transitions: A comment on the transitions research agenda. *Environmental Innovation and Societal Transitions*, **34**, 348–351. https://doi.org/10.1016/j.eist.2019.11.009

20. Aven, T. and E. Zio, 2021: Globalization and global risk: How risk analysis needs to be enhanced to be effective in confronting current threats. *Reliability Engineering & System Safety*, **205**, 107270. https://doi.org/10.1016/j.ress.2020.107270

21. Elsawah, S., T. Filatova, A.J. Jakeman, A. Kettner, M. Zellner, I. Athanasiadis, S. Hamilton, R. Axtell, D. Brown, J. Gilligan, M. Janssen, D. Robinson, J. Rozenberg, I. Ullah, and S. Lade, 2020: Eight grand challenges in socio-environmental systems modeling. *Socio-Environmental Systems Modelling*, **2**, 16226–16226. https://doi.org/10.18174/sesmo.2020a16226

22. Hino, M. and E. Nance, 2021: Five ways to ensure flood-risk research helps the most vulnerable. *Nature*, **595**, 27–29. https://doi.org/10.1038/d41586-021-01750-0

23. Levi, P.J., S.D. Kurland, M. Carbajales-Dale, J.P. Weyant, A.R. Brandt, and S.M. Benson, 2019: Macro-energy systems: Toward a new discipline. *Joule*, **3** (10), 2282–2286. https://doi.org/10.1016/j.joule.2019.07.017

24. Levin, S.A., J.M. Anderies, N. Adger, S. Barrett, E.M. Bennett, J.C. Cardenas, S.R. Carpenter, A.-S. Crépin, P. Ehrlich, J. Fischer, C. Folke, N. Kautsky, C. Kling, K. Nyborg, S. Polasky, M. Scheffer, K. Segerson, J. Shogren, J. van den Bergh, B. Walker, E.U. Weber, and J. Wilen, 2021: Governance in the face of extreme events: Lessons from evolutionary processes for structuring interventions, and the need to go beyond. *Ecosystems*, **25**, 697–711. https://doi.org/10.1007/s10021-021-00680-2

25. Markolf, S.A., M.V. Chester, D.A. Eisenberg, D.M. Iwaniec, C.I. Davidson, R. Zimmerman, T.R. Miller, B.L. Ruddell, and H. Chang, 2018: Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience. *Earth's Future*, **6** (12), 1638–1659. https://doi.org/10.1029/2018ef000926

26. Szostak, R., 2017: Stability, instability, and interdisciplinarity. *Issues in Interdisciplinary Studies*, **35**, 65–87. https://eric.ed.gov/?id=ej1193677

27. de Vos, L., H. Biemans, J.C. Doelman, E. Stehfest, and D.P. van Vuuren, 2021: Trade-offs between water needs for food, utilities, and the environment—A nexus quantification at different scales. *Environmental Research Letters*, **16** (11), 115003. https://doi.org/10.1088/1748-9326/ac2b5e

28. Drakes, O. and E. Tate, 2022: Social vulnerability in a multi-hazard context: A systematic review. *Environmental Research Letters*, **17**, 033001. https://doi.org/10.1088/1748-9326/ac5140

29. Zscheischler, J., S. Westra, B.J.J.M. van den Hurk, S.I. Seneviratne, P.J. Ward, A. Pitman, A. AghaKouchak, D.N. Bresch, M. Leonard, T. Wahl, and X. Zhang, 2018: Future climate risk from compound events. *Nature Climate Change*, **8** (6), 469–477. https://doi.org/10.1038/s41558-018-0156-3

30. Dearing, J.A., R. Wang, K. Zhang, J.G. Dyke, H. Haberl, M.S. Hossain, P.G. Langdon, T.M. Lenton, K. Raworth, S. Brown, J. Carstensen, M.J. Cole, S.E. Cornell, T.P. Dawson, C.P. Doncaster, F. Eigenbrod, M. Flörke, E. Jeffers, A.W. Mackay, B. Nykvist, and G.M. Poppy, 2014: Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change*, **28**, 227–238. https://doi.org/10.1016/j.gloenvcha.2014.06.012

31. Eriksen, S., E.L.F. Schipper, M. Scoville-Simonds, K. Vincent, H.N. Adam, N. Brooks, B. Harding, D. Khatri, L. Lenaerts, D. Liverman, M. Mills-Novoa, M. Mosberg, S. Movik, B. Muok, A. Nightingale, H. Ojha, L. Sygna, M. Taylor, C. Vogel, and J.J. West, 2021: Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development*, **141**, 105383. https://doi.org/10.1016/j.worlddev.2020.105383

32. Hallegatte, S. and N.L. Engle, 2019: The search for the perfect indicator: Reflections on monitoring and evaluation of resilience for improved climate risk management. *Climate Risk Management*, **23**, 1–6. https://doi.org/10.1016/j.crm.2018.12.001

33. Hallegatte, S., J. Rentschler, and J. Rozenberg, 2019: *Lifelines: The Resilient Infrastructure Opportunity*. World Bank Group, Washington, DC. http://hdl.handle.net/10986/31805

34. Lempert, R.J., 2021: Measuring global climate risk. *Nature Climate Change*, **11** (10), 805–806. https://doi.org/10.1038/s41558-021-01165-9

35. de Ruiter, M.C. and A.F. van Loon, 2022: The challenges of dynamic vulnerability and how to assess it. *iScience*, **25** (8). https://doi.org/10.1016/j.isci.2022.104720

36. Dolan, F., J. Lamontagne, R. Link, M. Hejazi, P. Reed, and J. Edmonds, 2021: Evaluating the economic impact of water scarcity in a changing world. *Nature Communications*, **12** (1), 1915. https://doi.org/10.1038/s41467-021-22194-0

37. Moallemi, E.A. and F.J. de Haan, 2019: *Modelling Transitions: Virtues, Vices, Visions of the Future*, 1st ed. Routledge, London, UK, 276 pp. https://doi.org/10.4324/9780429056574

38. Siders, A.R., M. Hino, and K.J. Mach, 2019: The case for strategic and managed climate retreat. *Science*, **365** (6455), 761. https://doi.org/10.1126/science.aax8346

39. Trutnevyte, E., L.F. Hirt, N. Bauer, A. Cherp, A. Hawkes, O.Y. Edelenbosch, S. Pedde, and D.P. Vuuren, 2019: Societal transformations in models for energy and climate policy: The ambitious next step. *One Earth*, **1** (4), 423–433. https://doi.org/10.1016/j.oneear.2019.12.002

40. Wible, B., 2021: Out of harm's way. *Science*, **372** (6548), 1274–1275. https://doi.org/10.1126/science.abi9209

41. Avelino, F., 2021: Theories of power and social change. Power contestations and their implications for research on social change and innovation. *Journal of Political Power*, **14** (3), 425–448. https://doi.org/10.1080/2158379x.2021.1875307

42. Jafino, B.A., J.H. Kwakkel, and B. Taebi, 2021: Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda. *WIREs Climate Change*, **12** (4), e721. https://doi.org/10.1002/wcc.721

43. Wyborn, C., A. Datta, J. Montana, M. Ryan, P. Leith, B. Chaffin, C. Miller, and L. van Kerkhoff, 2019: Co-producing sustainability: Reordering the governance of science, policy, and practice. *Annual Review of Environment and Resources*, **44** (1), 319–346. https://doi.org/10.1146/annurev-environ-101718-033103

44. Filatova, T., J.G. Polhill, and S. van Ewijk, 2016: Regime shifts in coupled socio-environmental systems: Review of modelling challenges and approaches. *Environmental Modelling & Software*, **75**, 333–347. https://doi.org/10.1016/j.envsoft.2015.04.003

45. Gold, D.F., P.M. Reed, D.E. Gorelick, and G.W. Characklis, 2022: Power and pathways: Exploring robustness, cooperative stability, and power relationships in regional infrastructure investment and water supply management portfolio pathways. *Earth's Future*, **10** (2), e2021EF002472. https://doi.org/10.1029/2021ef002472

46. Iwanaga, T., H.-H. Wang, S.H. Hamilton, V. Grimm, T.E. Koralewski, A. Salado, S. Elsawah, S. Razavi, J. Yang, P. Glynn, J. Badham, A. Voinov, M. Chen, W.E. Grant, T.R. Peterson, K. Frank, G. Shenk, C.M. Barton, A.J. Jakeman, and J.C. Little, 2021: Socio-technical scales in socio-environmental modeling: Managing a system-of-systems modeling approach. *Environmental Modelling & Software*, **135**, 104885. https://doi.org/10.1016/j.envsoft.2020.104885

47. Lamontagne, J.R., P.M. Reed, R. Link, K.V. Calvin, L.E. Clarke, and J.A. Edmonds, 2018: Large ensemble analytic framework for consequence-driven discovery of climate change scenarios. *Earth's Future*, **6** (3), 488–504. https://doi.org/10.1002/2017ef000701

48. Kasprzyk, J.R., S. Nataraj, P.M. Reed, and R.J. Lempert, 2013: Many objective robust decision making for complex environmental systems undergoing change. *Environmental Modelling & Software*, **42**, 55–71. https://doi.org/10.1016/j.envsoft.2012.12.007

49. Lempert, R.J., 2002: A new decision sciences for complex systems. *Proceedings of the National Academy of Sciences of the United States of America*, **99** (suppl_3), 7309–7313. https://doi.org/10.1073/pnas.082081699

50. Walker, W.E., M. Haasnoot, and J.H. Kwakkel, 2013: Adapt or perish: A review of planning approaches for adaptation under deep uncertainty. *Sustainability*, **5** (3), 955–979. https://doi.org/10.3390/su5030955

51. Walker, W.E., P. Harremoës, J. Rotmans, J.P. van der Sluijs, M.B. van Asselt, P. Janssen, and M.P. Krayer von Krauss, 2003: Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment*, **4** (1), 5–17. https://doi.org/10.1076/iaij.4.1.5.16466

52. Bankes, S., 1993: Exploratory modeling for policy analysis. *Operations Research*, **41** (3), 435–449. https://doi.org/10.1287/opre.41.3.435

53. Marchau, V.A.W.J., W.E. Walker, P.J.T.M. Bloemen, and S.W. Popper, 2019: *Decision Making Under Deep Uncertainty*. Springer, Cham, Switzerland, 405 pp. https://doi.org/10.1007/978-3-030-05252-2

54. Moallemi, E.A., J. Kwakkel, F.J. de Haan, and B.A. Bryan, 2020: Exploratory modeling for analyzing coupled human-natural systems under uncertainty. *Global Environmental Change*, **65**, 102186. https://doi.org/10.1016/j.gloenvcha.2020.102186

55. Bryant, B.P. and R.J. Lempert, 2010: Thinking inside the box: A participatory, computer-assisted approach to scenario discovery. *Technological Forecasting and Social Change*, **77** (1), 34–49. https://doi.org/10.1016/j.techfore.2009.08.002

56. Hadjimichael, A., J. Quinn, E. Wilson, P. Reed, L. Basdekas, D. Yates, and M. Garrison, 2020: Defining robustness, vulnerabilities, and consequential scenarios for diverse stakeholder interests in institutionally complex river basins. *Earth's Future*, **8** (7), e2020EF001503. https://doi.org/10.1029/2020ef001503

57. Popper, S.W., 2019: Robust decision making and scenario discovery in the absence of formal models. *Futures & Foresight Science*, **1** (3-4), e22. https://doi.org/10.1002/ffo2.22

58. Kopp, R.E., E.A. Gilmore, C.M. Little, J. Lorenzo-Trueba, V.C. Ramenzoni, and W.V. Sweet, 2019: Usable science for managing the risks of sea-level rise. *Earth's Future*, **7** (12), 1235–1269. https://doi.org/10.1029/2018ef001145

59. Brelsford, C., A. Jones, M. Allen-Dumas, M. Bukovsky, I. Dronova, T. Hong, D. Iwaniec, S. Markolf, M. Newcomer, P. Nico, D. Rastogi, S. Reid, K. Sparks, J. Tucillo, and Z. Zheng, 2021: Workshop Report: Multi-Sectoral Urban Interactions: Fundamental Science Needs to Inform Pathways to More Resilient Communities in a Changing Climate. MultiSector Dynamics Community of Practice. https://multisectordynamics.org/working-groups/urban/workshop-report-multi-sectoral-urban-interactions/

60. Mytton, D., 2021: Data centre water consumption. *npj Clean Water*, **4** (1), 11. https://doi.org/10.1038/s41545-021-00101-w

61. Masanet, E., A. Shehabi, N. Lei, S. Smith, and J. Koomey, 2020: Recalibrating global data center energy-use estimates. *Science*, **367** (6481), 984–986. https://doi.org/10.1126/science.aba3758

62. Siddik, M.A.B., A. Shehabi, and L. Marston, 2021: The environmental footprint of data centers in the United States. *Environmental Research Letters*, **16** (6), 064017. https://doi.org/10.1088/1748-9326/abfba1

63. Whitehead, B., D. Andrews, A. Shah, and G. Maidment, 2014: Assessing the environmental impact of data centres part 1: Background, energy use and metrics. *Building and Environment*, **82**, 151–159. https://doi.org/10.1016/j.buildenv.2014.08.021

64. Kenney, D.S., 2005: Prior appropriation and water rights reform in the western United States. In: *Water Rights Reform: Lessons for Institutional Design*. Bruns, B.R., C. Ringler, and R.S. Meinzen-Dick, Eds. International Food Policy Research Institute, Washington, DC. https://doi.org/10.2499/0896297497.ch7

65. Anguelovski, I., L. Shi, E. Chu, D. Gallagher, K. Goh, Z. Lamb, K. Reeve, and H. Teicher, 2016: Equity impacts of urban land use planning for climate adaptation: Critical perspectives from the global north and south. *Journal of Planning Education and Research*, **36** (3), 333–348. https://doi.org/10.1177/0739456x16645166

66. Chen, T.H.Y. and B. Lee, 2022: Income-based inequality in post-disaster migration is lower in high resilience areas: Evidence from U.S. internal migration. *Environmental Research Letters*, **17** (3), 034043. https://doi.org/10.1088/1748-9326/ac5692

67. Gonzalez, C., 2021: Racial capitalism, climate justice, and climate displacement. *Oñati Socio-Legal Series*, **11** (1), 108–147. https://doi.org/10.35295/osls.iisl/0000-0000-0000-1137

68. Knighton, J., K. Hondula, C. Sharkus, C. Guzman, and R. Elliott, 2021: Flood risk behaviors of United States riverine metropolitan areas are driven by local hydrology and shaped by race. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (13), e2016839118. https://doi.org/10.1073/pnas.2016839118

69. Pörtner, H.-O., D.C. Roberts, H. Adams, I. Adelekan, C. Adler, et al., 2022: Technical summary. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, and A. Okem, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 37–118. https://doi.org/10.1017/9781009325844.002

70. Prins, S.J. and B. Story, 2020: Connecting the dots between mass incarceration, health inequity, and climate change. *American Journal of Public Health*, **110** (S1), S35–S36. https://doi.org/10.2105/ajph.2019.305470

71. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

72. Amorim-Maia, A.T., I. Anguelovski, E. Chu, and J. Connolly, 2022: Intersectional climate justice: A conceptual pathway for bridging adaptation planning, transformative action, and social equity. *Urban Climate*, **41**, 101053. https://doi.org/10.1016/j.uclim.2021.101053

73. Anguelovski, I., A.L. Brand, J.J.T. Connolly, E. Corbera, P. Kotsila, J. Steil, M. Garcia-Lamarca, M. Triguero-Mas, H. Cole, F. Baró, J. Langemeyer, C.P. del Pulgar, G. Shokry, F. Sekulova, and L. Argüelles Ramos, 2020: Expanding the boundaries of justice in urban greening scholarship: Toward an emancipatory, antisubordination, intersectional, and relational approach. *Annals of the American Association of Geographers*, **110** (6), 1743–1769. https://doi.org/10.1080/24694452.2020.1740579

74. Kuran, C.H.A., C. Morsut, B.I. Kruke, M. Krüger, L. Segnestam, K. Orru, T.O. Nævestad, M. Airola, J. Keränen, F. Gabel, S. Hansson, and S. Torpan, 2020: Vulnerability and vulnerable groups from an intersectionality perspective. *International Journal of Disaster Risk Reduction*, **50**, 101826. https://doi.org/10.1016/j.ijdrr.2020.101826

75. Pulido, L., 2017: Geographies of race and ethnicity II: Environmental racism, racial capitalism and state-sanctioned violence. *Progress in Human Geography*, **41** (4), 524–533. https://doi.org/10.1177/0309132516646495

76. Stone, K., N. Blinn, and R. Spencer, 2022: Mental health impacts of climate change on women: A scoping review. *Current Environmental Health Reports*, **9** (2), 228–243. https://doi.org/10.1007/s40572-022-00346-8

77. Bigger, P. and N. Millington, 2020: Getting soaked? Climate crisis, adaptation finance, and racialized austerity. *Environment and Planning E: Nature and Space*, **3** (3), 601–623. https://doi.org/10.1177/2514848619876539

78. Huang, X. and C. Wang, 2020: Estimates of exposure to the 100-year floods in the conterminous United States using national building footprints. *International Journal of Disaster Risk Reduction*, **50**, 101731. https://doi.org/10.1016/j.ijdrr.2020.101731

79. Tate, E., M.A. Rahman, C.T. Emrich, and C.C. Sampson, 2021: Flood exposure and social vulnerability in the United States. *Natural Hazards*, **106** (1), 435–457. https://doi.org/10.1007/s11069-020-04470-2

80. USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/nca4.2018

81. Siders, A.R. and J.M. Keenan, 2020: Variables shaping coastal adaptation decisions to armor, nourish, and retreat in North Carolina. *Ocean & Coastal Management*, **183**, 105023. https://doi.org/10.1016/j.ocecoaman.2019.105023

82. Barile, J.P., S.B. Binder, and C.K. Baker, 2020: Recovering after a natural disaster: Differences in quality of life across three communities after Hurricane Sandy. *Applied Research in Quality of Life*, **15** (4), 1151–1159. https://doi.org/10.1007/s11482-019-09722-3

83. Mach, K.J., C.M. Kraan, M. Hino, A.R. Siders, E.M. Johnston, and C.B. Field, 2019: Managed retreat through voluntary buyouts of flood-prone properties. *Science Advances*, **5** (10), 8995. https://doi.org/10.1126/sciadv.aax8995

84. McGhee, D.J., S.B. Binder, and E.A. Albright, 2020: First, do no harm: Evaluating the vulnerability reduction of post-disaster home buyout programs. *Natural Hazards Review*, **21** (1), 05019002. https://doi.org/10.1061/(asce)nh.1527-6996.0000337

85. Elliott, J.R., K. Loughran, and P.L. Brown, 2021: Divergent residential pathways from flood-prone areas: How neighborhood inequalities are shaping urban climate adaptation. *Social Problems*, spab059. https://doi.org/10.1093/socpro/spab059

86. Turek-Hankins, L.L., M. Hino, and K.J. Mach, 2020: Risk screening methods for extreme heat: Implications for equity-oriented adaptation. *PLoS ONE*, **15** (11), e0240841. https://doi.org/10.1371/journal.pone.0240841

87. Beckage, B., K. Lacasse, J.M. Winter, L.J. Gross, N. Fefferman, F.M. Hoffman, S.S. Metcalf, T. Franck, E. Carr, A. Zia, and A. Kinzig, 2020: The Earth has humans, so why don't our climate models? *Climatic Change*, **163** (1), 181–188. https://doi.org/10.1007/s10584-020-02897-x

88. Moore, F.C., K. Lacasse, K.J. Mach, Y.A. Shin, L.J. Gross, and B. Beckage, 2022: Determinants of emissions pathways in the coupled climate–social system. *Nature*, **603** (7899), 103–111. https://doi.org/10.1038/s41586-022-04423-8

89. Palmer, P.I. and M.J. Smith, 2014: Earth systems: Model human adaptation to climate change. *Nature*, **512** (7515), 365–366. https://doi.org/10.1038/512365a

90. Rising, J., M. Tedesco, F. Piontek, and D.A. Stainforth, 2022: The missing risks of climate change. *Nature*, **610** (7933), 643–651. https://doi.org/10.1038/s41586-022-05243-6

91. Cain, B.E., E.R. Gerber, and I. Hui, 2020: Getting bipartisan support for sea level rise adaptation policies. *Ocean & Coastal Management*, **197**, 105298. https://doi.org/10.1016/j.ocecoaman.2020.105298

92. Willison, C.E., P.M. Singer, M.S. Creary, S. Vaziri, J. Stott, and S.L. Greer, 2021: How do you solve a problem like Maria? The politics of disaster response in Puerto Rico, Florida and Texas. *World Medical & Health Policy*, **14** (3), 490–506. https://doi.org/10.1002/wmh3.476

93. Garrick, D., L. De Stefano, W. Yu, I. Jorgensen, E. O'Donnell, L. Turley, I. Aguilar-Barajas, X. Dai, R. de Souza Leão, B. Punjabi, B. Schreiner, J. Svensson, and C. Wight, 2019: Rural water for thirsty cities: A systematic review of water reallocation from rural to urban regions. *Environmental Research Letters*, **14** (4), 043003. https://doi.org/10.1088/1748-9326/ab0db7

94. Kelly-Reif, K. and S. Wing, 2016: Urban-rural exploitation: An underappreciated dimension of environmental injustice. *Journal of Rural Studies*, **47**, 350–358. https://doi.org/10.1016/j.jrurstud.2016.03.010

95. Shi, L., S. Ahmad, P. Shukla, and S. Yupho, 2021: Shared injustice, splintered solidarity: Water governance across urban-rural divides. *Global Environmental Change*, **70**, 102354. https://doi.org/10.1016/j.gloenvcha.2021.102354

96. Bukvic, A. and J. Harrald, 2019: Rural versus urban perspective on coastal flooding: The insights from the U.S. Mid-Atlantic communities. *Climate Risk Management*, **23**, 7–18. https://doi.org/10.1016/j.crm.2018.10.004

97. Hansen, G. and W. Cramer, 2015: Global distribution of observed climate change impacts. *Nature Climate Change*, **5** (3), 182–185. https://doi.org/10.1038/nclimate2529

98. Friel, S., D. Vlahov, and R.M. Buckley, 2011: No data, no problem, no action: Addressing urban health inequity in the 21st century. *Journal of Urban Health*, **88** (5), 858. https://doi.org/10.1007/s11524-011-9616-z

99. Bullard, R.D. and B. Wright, 2012: *The Wrong Complexion for Protection: How the Government Response to Disaster Endangers African American Communities*. New York University Press. https://doi.org/10.18574/nyu/9780814799932.001.0001

100. Andrews, C.J., 2020: Toward a research agenda on climate-related migration. *Journal of Industrial Ecology*, **24** (2), 331–341. https://doi.org/10.1111/jiec.13005

101. Sastry, N. and J. Gregory, 2014: The location of displaced New Orleans residents in the year after Hurricane Katrina. *Demography*, **51** (3), 753–775. https://doi.org/10.1007/s13524-014-0284-y

102. Beam, A., 2019: Chico didn't burn but Camp fire brought a new way of life. *The Press Democrat*, November 7, 2019. https://www.pressdemocrat.com/article/news/chico-didnt-burn-but-camp-fire-brought-a-new-way-of-life/

103. Spearing, L.A. and K.M. Faust, 2020: Cascading system impacts of the 2018 Camp Fire in California: The interdependent provision of infrastructure services to displaced populations. *International Journal of Disaster Risk Reduction*, **50**, 101822. https://doi.org/10.1016/j.ijdrr.2020.101822

104. Lefebvre, B., 2021: How 'climate migrants' are roiling American politics. *POLITICO*. https://www.politico.com/news/magazine/2021/11/27/how-climate-migrants-are-roiling-american-politics-523295

105. Rainey, J., 2019: Fire turns Chico, California, into a boomtown, but at what cost? *NBC News*, January 20, 2019. https://www.nbcnews.com/news/us-news/fire-turns-chico-california-boomtown-what-cost-n960081

106. Klein, N., 2021: A climate dystopia in Northern California. *The Intercept*, May 7 2021. https://theintercept.com/2021/05/07/california-fires-chico-housing-real-estate/

107. Wedgeworth, C., 2019: Hottest U.S. real estate market for December 2018 is Chico, CA. *Realtor*, January 9, 2019. https://www.realtor.com/news/trends/december-2018-hottest-real-estate-markets-wildfire-boosts-chico/

108. Curtis, K.J., J. DeWaard, E. Fussell, and R.A. Rosenfeld, 2020: Differential recovery migration across the rural–urban gradient: Minimal and short-term population gains for rural disaster-affected Gulf Coast counties. *Rural Sociology*, **85** (4), 856–898. https://doi.org/10.1111/ruso.12305

109. de Koning, K. and T. Filatova, 2020: Repetitive floods intensify outmigration and climate gentrification in coastal cities. *Environmental Research Letters*, **15** (3), 034008. https://doi.org/10.1088/1748-9326/ab6668

110. Friedman, N., 2021: The pandemic ignited a housing boom—But it's different from the last one. *The Wall Street Journal*, March 15, 2021. https://www.wsj.com/articles/the-pandemic-ignited-a-housing-boombut-its-different-from-the-last-one-11615824558

111. Patino, M., A. Kessler, S. Holder, J. Gu, and M. Rojanasakul, 2021: More Americans are leaving cities, but don't call it an urban exodus. *Bloomberg*, April 26, 2021. https://www.bloomberg.com/graphics/2021-citylab-how-americans-moved/

112. Moser, S.C. and J.A.F. Hart, 2015: The long arm of climate change: Societal teleconnections and the future of climate change impacts studies. *Climatic Change*, **129** (1), 13–26. https://doi.org/10.1007/s10584-015-1328-z

113. Zoraghein, H. and B.C. O'Neill, 2020: A spatial population downscaling model for integrated human-environment analysis in the United States. *Demographic Research*, **43**, 1563–1606. https://doi.org/10.4054/demres.2020.43.54

114. Field, C.B., V.R. Barros, K.J. Mach, M.D. Mastrandrea, M. van Aalst, W.N. Adger, D.J. Arent, J. Barnett, R. Betts, T.E. Bilir, J. Birkmann, J. Carmin, D.D. Chadee, A.J. Challinor, M. Chatterjee, W. Cramer, D.J. Davidson, Y.O. Estrada, J.P. Gattuso, Y. Hijioka, O. Hoegh-Guldberg, H.Q. Huang, G.E. Insarov, R.N. Jones, R.S. Kovats, P.R. Lankao, J.N. Larsen, I.J. Losada, J.A. Marengo, R.F. McLean, L.O. Mearns, R. Mechler, J.F. Morton, I. Niang, T. Oki, J.M. Olwoch, M. Opondo, E.S. Poloczanska, H.O. Pörtner, M.H. Redsteer, A. Reisinger, A. Revi, D.N. Schmidt, M.R. Shaw, W. Solecki, D.A. Stone, J.M.R. Stone, K.M. Strzepek, A.G. Suarez, P. Tschakert, R. Valentini, S. Vicuña, A. Villamizar, K.E. Vincent, R. Warren, L.L. White, T.J. Wilbanks, P.P. Wong, and G.W. Yohe, 2014: Technical summary. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 35–94. https://www.ipcc.ch/report/ar5/wg2/

115. Hulme, M., 2018: "Gaps" in climate change knowledge: Do they exist? Can they be filled? *Environmental Humanities*, **10** (1), 330–337. https://doi.org/10.1215/22011919-4385599

116. Stern, M.J., D.D. Briske, and A.M. Meadow, 2021: Opening learning spaces to create actionable knowledge for conservation. *Conservation Science and Practice*, **3** (5), e378. https://doi.org/10.1111/csp2.378

117. Lubell, M. and T.H. Morrison, 2021: Institutional navigation for polycentric sustainability governance. *Nature Sustainability*, **4** (8), 664–671. https://doi.org/10.1038/s41893-021-00707-5

118. Härtel, C.E.J. and G.I. Pearman, 2010: Understanding and responding to the climate change issue: Towards a whole-of-science research agenda. *Journal of Management & Organization*, **16** (1), 16–47. https://doi.org/10.5172/jmo.16.1.16

119. Lemos, M.C., H. Eakin, L. Dilling, and J. Worl, 2019: Social sciences, weather, and climate change. *Meteorological Monographs*, **59**, 26.1–26.25. https://doi.org/10.1175/amsmonographs-d-18-0011.1

120. Meinke, H., R. Nelson, P. Kokic, R. Stone, R. Selvaraju, and W. Baethgen, 2006: Actionable climate knowledge: From analysis to synthesis. *Climate Research*, **33**, 101–110. https://doi.org/10.3354/cr033101

121. Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756. https://doi.org/10.1038/nature08823

122. Tribbia, J. and S.C. Moser, 2008: More than information: What coastal managers need to plan for climate change. *Environmental Science & Policy*, **11** (4), 315–328. https://doi.org/10.1016/j.envsci.2008.01.003

123. Liu, J., T. Dietz, S.R. Carpenter, M. Alberti, C. Folke, E. Moran, A.N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C.L. Redman, S.H. Schneider, and W.W. Taylor, 2007: Complexity of coupled human and natural systems. *Science*, **317** (5844), 1513–1516. https://doi.org/10.1126/science.1144004

124. Polk, M., 2015: Transdisciplinary co-production: Designing and testing a transdisciplinary research framework for societal problem solving. *Futures*, **65**, 110–122. https://doi.org/10.1016/j.futures.2014.11.001

125. Jagannathan, K., A.D. Jones, and I. Ray, 2021: The making of a metric: Co-producing decision-relevant climate science. *Bulletin of the American Meteorological Society*, **102** (8), E1579–E1590. https://doi.org/10.1175/bams-d-19-0296.1

126. Miralles-Wilhelm, F., 2016: Development and application of integrative modeling tools in support of food-energy-water nexus planning—A research agenda. *Journal of Environmental Studies and Sciences*, **6** (1), 3–10. https://doi.org/10.1007/s13412-016-0361-1

127. Moss, R.H., S. Avery, K. Baja, M. Burkett, A.M. Chischilly, J. Dell, P.A. Fleming, K. Geil, K. Jacobs, A. Jones, K. Knowlton, J. Koh, M.C. Lemos, J. Melillo, R. Pandya, T.C. Richmond, L. Scarlett, J. Snyder, M. Stults, A. Waple, J. Whitehead, D. Zarrilli, J. Fox, A. Ganguly, L. Joppa, S. Julius, P. Kirshen, R. Kreutter, A. McGovern, R. Meyer, J. Neumann, W. Solecki, J. Smith, P. Tissot, G. Yohe, and R. Zimmerman, 2019: A framework for sustained climate assessment in the United States. *Bulletin of the American Meteorological Society*, **100** (5), 897–907. https://doi.org/10.1175/bams-d-19-0130.1

128. Biehl, P.F., S. Crate, M. Gardezi, L. Hamilton, S.L. Harlan, C. Hritz, B. Hubbell, T.A. Kohler, N. Peterson, and J. Silva, 2018: Innovative Tools, Methods, and Analysis: Social Science Perspectives on Climate Change, Part 3. U.S. Global Change Research Program, Social Science Coordinating Committee, Washington, DC. https://www.globalchange.gov/sites/globalchange/files/Methods_SSCC.pdf

129. Krauß, W. and S. Bremer, 2020: The role of place-based narratives of change in climate risk governance. *Climate Risk Management*, **28**, 100221. https://doi.org/10.1016/j.crm.2020.100221

130. Moezzi, M., K.B. Janda, and S. Rotmann, 2017: Using stories, narratives, and storytelling in energy and climate change research. *Energy Research & Social Science*, **31**, 1–10. https://doi.org/10.1016/j.erss.2017.06.034

131. Calvin, K., P. Patel, L. Clarke, G. Asrar, B. Bond-Lamberty, R.Y. Cui, A. Di Vittorio, K. Dorheim, J. Edmonds, C. Hartin, M. Hejazi, R. Horowitz, G. Iyer, P. Kyle, S. Kim, R. Link, H. McJeon, S.J. Smith, A. Snyder, S. Waldhoff, and M. Wise, 2019: GCAM v5.1: Representing the linkages between energy, water, land, climate, and economic systems. *Geoscientific Model Development*, **12** (2), 677–698. https://doi.org/10.5194/gmd-12-677-2019

132. Vogel, J., E. McNie, and D. Behar, 2016: Co-producing actionable science for water utilities. *Climate Services*, **2–3**, 30–40. https://doi.org/10.1016/j.cliser.2016.06.003

133. Epstein, S.A., S.-M. Lee, A.S. Katzenstein, M. Carreras-Sospedra, X. Zhang, S.C. Farina, P. Vahmani, P.M. Fine, and G. Ban-Weiss, 2017: Air-quality implications of widespread adoption of cool roofs on ozone and particulate matter in southern California. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (34), 8991–8996. https://doi.org/10.1073/pnas.1703560114

134. Vahmani, P. and A.D. Jones, 2017: Water conservation benefits of urban heat mitigation. *Nature Communications*, **8** (1), 1072. https://doi.org/10.1038/s41467-017-01346-1

135. Vahmani, P., F. Sun, A. Hall, and G. Ban-Weiss, 2016: Investigating the climate impacts of urbanization and the potential for cool roofs to counter future climate change in Southern California. *Environmental Research Letters*, **11** (12), 124027. https://doi.org/10.1088/1748-9326/11/12/124027

136. Szinai, J.K., R. Deshmukh, D.M. Kammen, and A.D. Jones, 2020: Evaluating cross-sectoral impacts of climate change and adaptations on the energy-water nexus: A framework and California case study. *Environmental Research Letters*, **15** (12), 124065. https://doi.org/10.1088/1748-9326/abc378

137. Scanlon, B.R., B.L. Ruddell, P.M. Reed, R.I. Hook, C. Zheng, V.C. Tidwell, and S. Siebert, 2017: The food-energy-water nexus: Transforming science for society. *Water Resources Research*, **53** (5), 3550–3556. https://doi.org/10.1002/2017wr020889

138. Ford, J.D., N. King, E.K. Galappaththi, T. Pearce, G. McDowell, and S.L. Harper, 2020: The resilience of Indigenous peoples to environmental change. *One Earth*, **2** (6), 532–543. https://doi.org/10.1016/j.oneear.2020.05.014

139. Petzold, J., N. Andrews, J.D. Ford, C. Hedemann, and J.C. Postigo, 2020: Indigenous knowledge on climate change adaptation: A global evidence map of academic literature. *Environmental Research Letters*, **15** (11), 113007. https://doi.org/10.1088/1748-9326/abb330

140. Voinov, A. and E.B. Gaddis, 2017: Ch. 3. Values in participatory modeling: Theory and practice. In: *Environmental Modeling with Stakeholders: Theory, Methods, and Applications*. Gray, S., M. Paolisso, R. Jordan, and S. Gray, Eds. Springer, Cham, Switzerland, 47–63. https://doi.org/10.1007/978-3-319-25053-3_3

141. Bremer, S., M.M. Haque, S.B. Aziz, and S. Kvamme, 2019: 'My new routine': Assessing the impact of citizen science on climate adaptation in Bangladesh. *Environmental Science & Policy*, **94**, 245–257. https://doi.org/10.1016/j.envsci.2018.12.029

142. Cooper, C.B., J. Shirk, and B. Zuckerberg, 2014: The invisible prevalence of citizen science in global research: Migratory birds and climate change. *PLoS ONE*, **9** (9), e106508. https://doi.org/10.1371/journal.pone.0106508

143. Danielsen, F., K. Pirhofer-Walzl, T.P. Adrian, D.R. Kapijimpanga, N.D. Burgess, P.M. Jensen, R. Bonney, M. Funder, A. Landa, N. Levermann, and J. Madsen, 2014: Linking public participation in scientific research to the indicators and needs of international environmental agreements. *Conservation Letters*, **7** (1), 12–24. https://doi.org/10.1111/conl.12024

144. Rubio-Iglesias, J.M., T. Edovald, R. Grew, T. Kark, A.E. Kideys, T. Peltola, and H. Volten, 2020: Citizen science and environmental protection agencies: Engaging citizens to address key environmental challenges. *Frontiers in Climate*, **2**, 600998. https://doi.org/10.3389/fclim.2020.600998

145. Weatherhead, E., S. Gearheard, and R.G. Barry, 2010: Changes in weather persistence: Insight from Inuit knowledge. *Global Environmental Change*, **20** (3), 523–528. https://doi.org/10.1016/j.gloenvcha.2010.02.002

146. Bremer, S. and S. Meisch, 2017: Co-production in climate change research: Reviewing different perspectives. *WIREs Climate Change*, **8** (6), e482. https://doi.org/10.1002/wcc.482

147. Lemos, M.C., J.C. Arnott, N.M. Ardoin, K. Baja, A.T. Bednarek, A. Dewulf, C. Fieseler, K.A. Goodrich, K. Jagannathan, N. Klenk, K.J. Mach, A.M. Meadow, R. Meyer, R. Moss, L. Nichols, K.D. Sjostrom, M. Stults, E. Turnhout, C. Vaughan, G. Wong-Parodi, and C. Wyborn, 2018: To co-produce or not to co-produce. *Nature Sustainability*, **1** (12), 722–724. https://doi.org/10.1038/s41893-018-0191-0

148. Mach, K.J., M.C. Lemos, A.M. Meadow, C. Wyborn, N. Klenk, J.C. Arnott, N.M. Ardoin, C. Fieseler, R.H. Moss, L. Nichols, M. Stults, C. Vaughan, and G. Wong-Parodi, 2020: Actionable knowledge and the art of engagement. *Current Opinion in Environmental Sustainability*, **42**, 30–37. https://doi.org/10.1016/j.cosust.2020.01.002

149. Miller, C.A. and C. Wyborn, 2020: Co-production in global sustainability: Histories and theories. *Environmental Science & Policy*, **113**, 88–95. https://doi.org/10.1016/j.envsci.2018.01.016

150. Chambers, J.M., C. Wyborn, M.E. Ryan, R.S. Reid, M. Riechers, A. Serban, N.J. Bennett, C. Cvitanovic, M.E. Fernández-Giménez, K.A. Galvin, B.E. Goldstein, N.L. Klenk, M. Tengö, R. Brennan, J.J. Cockburn, R. Hill, C. Munera, J.L. Nel, H. Österblom, A.T. Bednarek, E.M. Bennett, A. Brandeis, L. Charli-Joseph, P. Chatterton, K. Curran, P. Dumrongrojwatthana, A.P. Durán, S.J. Fada, J.-D. Gerber, J.M.H. Green, A.M. Guerrero, T. Haller, A.-I. Horcea-Milcu, B. Leimona, J. Montana, R. Rondeau, M. Spierenburg, P. Steyaert, J.G. Zaehringer, R. Gruby, J. Hutton, and T. Pickering, 2021: Six modes of co-production for sustainability. *Nature Sustainability*, **4** (11), 983–996. https://doi.org/10.1038/s41893-021-00755-x

151. Jagannathan, K., J.C. Arnott, C. Wyborn, N. Klenk, K.J. Mach, R.H. Moss, and K.D. Sjostrom, 2020: Great expectations? Reconciling the aspiration, outcome, and possibility of co-production. *Current Opinion in Environmental Sustainability*, **42**, 22–29. https://doi.org/10.1016/j.cosust.2019.11.010

152. Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, **62**, 102071. https://doi.org/10.1016/j.gloenvcha.2020.102071

153. Cash, D.W., W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, D.H. Guston, J. Jäger, and R.B. Mitchell, 2003: Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America*, **100** (14), 8086–8091. https://doi.org/10.1073/pnas.1231332100

154. Lemos, M.C., C.J. Kirchhoff, and V. Ramprasad, 2012: Narrowing the climate information usability gap. *Nature Climate Change*, **2** (11), 789–794. https://doi.org/10.1038/nclimate1614

155. Briley, L., D. Brown, and S.E. Kalafatis, 2015: Overcoming barriers during the co-production of climate information for decision-making. *Climate Risk Management*, **9**, 41–49. https://doi.org/10.1016/j.crm.2015.04.004

156. Voinov, A. and F. Bousquet, 2010: Modelling with stakeholders. *Environmental Modelling & Software*, **25** (11), 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007

157. Voinov, A., N. Kolagani, M.K. McCall, P.D. Glynn, M.E. Kragt, F.O. Ostermann, S.A. Pierce, and P. Ramu, 2016: Modelling with stakeholders – Next generation. *Environmental Modelling & Software*, **77**, 196–220. https://doi.org/10.1016/j.envsoft.2015.11.016

158. County of Los Angeles, 2021: LA County Climate Vulnerability Assessment. County of Los Angeles, LA County Chief Sustainability Office, Los Angeles, CA. https://ceo.lacounty.gov/wp-content/uploads/2021/10/LA-County-Climate-Vulnerability-Assessment-1.pdf

159. California Coastal Commission, 2020: California Coastal Commission Final Strategic Plan 2021–2025. State of California, California Natural Resources Agency, San Francisco, CA. https://documents.coastal.ca.gov/assets/strategicplan/ccc_strategic_plan_adopted_11.06.20_rev.pdf

160. Stanton, M.C.B. and K. Roelich, 2021: Decision making under deep uncertainties: A review of the applicability of methods in practice. *Technological Forecasting and Social Change*, **171**, 120939. https://doi.org/10.1016/j.techfore.2021.120939

161. Werners, S.E., R.M. Wise, J.R.A. Butler, E. Totin, and K. Vincent, 2021: Adaptation pathways: A review of approaches and a learning framework. *Environmental Science & Policy*, **116**, 266–275. https://doi.org/10.1016/j.envsci.2020.11.003

162. Cobb, A.N. and J.L. Thompson, 2012: Climate change scenario planning: A model for the integration of science and management in environmental decision-making. *Environmental Modelling & Software*, **38**, 296–305. https://doi.org/10.1016/j.envsoft.2012.06.012

163. Lawrence, D.J. and A.N. Runyon, 2019: Implications of Climate Change for the Water Supply of the Chisos Mountains Developed Area. Natural Resource Report NPS/NRSS/CCRP/NRR—2019/2045. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://irma.nps.gov/datastore/downloadfile/631301

164. Miller, B.W., G.W. Schuurman, A.J. Symstad, A.N. Runyon, and B.C. Robb, 2022: Conservation under uncertainty: Innovations in participatory climate change scenario planning from U.S. national parks. *Conservation Science and Practice*, **4** (3), 12633. https://doi.org/10.1111/csp2.12633

165. Runyon, A.N., A.R. Carlson, J. Gross, D.J. Lawrence, and G.W. Schuurman, 2020: Repeatable approaches to work with scientific uncertainty and advance climate change adaptation in US national parks. *Parks Stewardship Forum*, **36** (1), 98–104. https://doi.org/10.5070/p536146402

166. Bremer, S., A. Wardekker, S. Dessai, S. Sobolowski, R. Slaattelid, and J. van der Sluijs, 2019: Toward a multi-faceted conception of co-production of climate services. *Climate Services*, **13**, 42–50. https://doi.org/10.1016/j.cliser.2019.01.003

167. Vaughan, C., L. Buja, A. Kruczkiewicz, and L. Goddard, 2016: Identifying research priorities to advance climate services. *Climate Services*, **4**, 65–74. https://doi.org/10.1016/j.cliser.2016.11.004

168. Vaughan, C. and S. Dessai, 2014: Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews: Climate Change*, **5** (5), 587–603. https://doi.org/10.1002/wcc.290

169. Goodrich, K.A., K.D. Sjostrom, C. Vaughan, L. Nichols, A. Bednarek, and M.C. Lemos, 2020: Who are boundary spanners and how can we support them in making knowledge more actionable in sustainability fields? *Current Opinion in Environmental Sustainability*, **42**, 45–51. https://doi.org/10.1016/j.cosust.2020.01.001

170. Lemos, M.C., C.J. Kirchhoff, S.E. Kalafatis, D. Scavia, and R.B. Rood, 2014: Moving climate information off the shelf: Boundary chains and the role of Risas as adaptive organizations. *Weather, Climate, and Society*, **6** (2), 273–285. https://doi.org/10.1175/wcas-d-13-00044.1

171. Meadow, A.M. and G. Owen, 2021: Planning and Evaluating the Societal Impacts of Climate Change Research Projects: A Guidebook for Natural and Physical Scientists Looking to Make a Difference. University of Arizona, Tucson, AZ. https://doi.org/10.2458/10150.658313

172. Wong-Parodi, G., K.J. Mach, K. Jagannathan, and K.D. Sjostrom, 2020: Insights for developing effective decision support tools for environmental sustainability. *Current Opinion in Environmental Sustainability*, **42**, 52–59. https://doi.org/10.1016/j.cosust.2020.01.005

173. Miami-Dade County, 2022: Little River Adaptation Action Area [Website]. https://adaptation-action-area-in-little-river-mdc.hub.arcgis.com/

174. Harrison, T.R., A. Clark, A. Clement, J. Lombard, G. Maranto, A. Parrish, S. Purkis, M. Reamer, O. Collins, C. Lewis, M. Cruz, and A. Solache, 2022: Advancing a hyperlocal approach to community engagement in climate adaptation: Results from a South Florida pilot study in two communities. *PLoS Climate*, **1** (6), e0000041. https://doi.org/10.1371/journal.pclm.0000041

175. Miami-Dade County, 2021: Climate Action Strategy [Webpage]. https://www.miamidade.gov/global/economy/resilience/climate-strategy/home.page

176. Miami-Dade County, 2021: Miami-Dade County Sea Level Rise Strategy. Miami-Dade County. https://miami-dade-county-sea-level-rise-strategy-draft-mdc.hub.arcgis.com/

177. SFWMD, 2021: SFWMD seeking public input on draft sea level rise and flood resiliency plan. South Florida Water Management District, West Palm Beach, FL, November 29, 2021. https://www.sfwmd.gov/news-events/news/sfwmd-seeking-public-input-draft-sea-level-rise-and-flood-resiliency-plan

178. Troxler, T.G., A.C. Clement, Y. Arditi-Rocha, G. Beesing, M. Bhat, J. Bolson, C. Cabán-Alemán, K. Castillo, O. Collins, M. Cruz, A. Dodd, S.D. Evans, A.L. Fleming, C. Genatios, J. Gilbert, A. Hernandez, C. Holder, M. Ilcheva, E. Kelly, and E. Wheaton, 2021: A system for resilience learning: Developing a community-driven, multi-sector research approach for greater preparedness and resilience to long-term climate stressors and extreme events in the Miami metropolitan region. *Journal of Extreme Events*, **08** (03), 2150019. https://doi.org/10.1142/s2345737621500196

179. Tedesco, M., C.G. Hultquist, and A. Sherbinin, 2021: A new dataset integrating public socioeconomic, physical risk, and housing data for climate justice metrics: A test-case study in Miami. *Environmental Justice*, **15** (3), 149–159. https://doi.org/10.1089/env.2021.0059

180. Miami-Dade County, 2022: Planning for Sea Level Rise in the Little River Adaptation Action Area. Resilient 305: Adaptation Action Area in Little River. Miami-Dade County, Office of Resilience. https://adaptation-action-area-in-little-river-mdc.hub.arcgis.com/

181. Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group, 2020: Unified Sea Level Rise Projections: 2019 Update. Southeast Florida Regional Climate Change Compact, 36 pp. https://southeastfloridaclimatecompact.org/unified-sea-level-rise-projections/

182. Huitema, D., W.N. Adger, F. Berkhout, E. Massey, D. Mazmanian, S. Munaretto, R. Plummer, and C.C.J.A.M. Termeer, 2016: The governance of adaptation: Choices, reasons, and effects. Introduction to the Special Feature. *Ecology and Society*, **21** (3), 37. https://doi.org/10.5751/es-08797-210337

183. Reed, T., L.R. Mason, and C.C. Ekenga, 2020: Adapting to climate change in the Upper Mississippi River Basin: Exploring stakeholder perspectives on river system management and flood risk reduction. *Environmental Health Insights*, **14**, 1178630220984153. https://doi.org/10.1177/1178630220984153

184. Ulibarri, N. and N. Escobedo Garcia, 2020: Comparing complexity in watershed governance: The case of California. *Water*, **12** (3). https://doi.org/10.3390/w12030766

185. Moser, S.C., J.A. Ekstrom, J. Kim, and S. Heitsch, 2019: Adaptation finance archetypes: Local governments' persistent challenges of funding adaptation to climate change and ways to overcome them. *Ecology and Society*, **24** (2), 28. https://doi.org/10.5751/es-10980-240228

186. Fried, H., M. Hamilton, and R. Berardo, 2022: Closing integrative gaps in complex environmental governance systems. *Ecology and Society*, **27** (1). https://doi.org/10.5751/es-12996-270115

187. Munaretto, S., G. Siciliano, and M.E. Turvani, 2014: Integrating adaptive governance and participatory multicriteria methods: A framework for climate adaptation governance. *Ecology and Society*, **19** (2), 74. https://doi.org/10.5751/es-06381-190274

188. Bai, X., R.R.J. McAllister, R.M. Beaty, and B. Taylor, 2010: Urban policy and governance in a global environment: Complex systems, scale mismatches and public participation. *Current Opinion in Environmental Sustainability*, **2** (3), 129–135. https://doi.org/10.1016/j.cosust.2010.05.008

189. Folke, C., T. Hahn, P. Olsson, and J. Norberg, 2005: Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources*, **30** (1), 441–473. https://doi.org/10.1146/annurev.energy.30.050504.144511

190. Hurlbert, M.A. and J. Gupta, 2019: An institutional analysis method for identifying policy instruments facilitating the adaptive governance of drought. *Environmental Science & Policy*, **93**, 221–231. https://doi.org/10.1016/j.envsci.2018.09.017

191. Wheeler, S.M., 2008: State and municipal climate change plans: The first generation. *Journal of the American Planning Association*, **74** (4), 481–496. https://doi.org/10.1080/01944360802377973

192. Brown, A., A. Dayal, and C. Rumbaitis Del Rio, 2012: From practice to theory: Emerging lessons from Asia for building urban climate change resilience. *Environment and Urbanization*, **24** (2), 531–556. https://doi.org/10.1177/0956247812456490

193. Brown, A. and S. Kernaghan, 2011: Beyond climate-proofing: Taking an integrated approach to building climate resilience in Asian Cities. *Urbanisation and Global Environmental Change Viewpoints*, **6**, 4–7. https://www.acccrn.net/resources/beyond-climate-proofing-taking-integrated-approach-building-climate-resilience-asian

194. De Wandeler, K., 2014: Social resilience and urban growth: Exploring urban 'strategies' and 'tactics' in Bangkok and Colombo. In: *Proceedings of the International Conference on 'Cities, People and Places'*. Colombo, Sri Lanka, 31 October–2 November 2014, 23 pp. https://uom.lk/sites/default/files/cfc/files/ICCPP-2014%20%20Programme%20%26%20Abstract_0.pdf

195. Ekstrom, J. and S. Moser, 2013: Ch. 6. Institutions as key element to successful climate adaptation processes: Results from the San Francisco Bay Area. In: *Successful Adaptation to Climate Change*, 1st ed. Routledge, London, UK, 97–113. https://doi.org/10.4324/9780203593882

196. Oberlack, C., 2017: Diagnosing institutional barriers and opportunities for adaptation to climate change. *Mitigation and Adaptation Strategies for Global Change*, **22** (5), 805–838. https://doi.org/10.1007/s11027-015-9699-z

197. Antrobus, D., 2011: Smart green cities: From modernization to resilience? *Urban Research & Practice*, **4** (2), 207–214. https://doi.org/10.1080/17535069.2011.579777

198. Arellano-Gonzalez, J., A. AghaKouchak, M.C. Levy, Y. Qin, J. Burney, S.J. Davis, and F.C. Moore, 2021: The adaptive benefits of agricultural water markets in California. *Environmental Research Letters*, **16** (4), 044036. https://doi.org/10.1088/1748-9326/abde5b

199. Aylett, A., 2015: Institutionalizing the urban governance of climate change adaptation: Results of an international survey. *Urban Climate*, **14**, 4–16. https://doi.org/10.1016/j.uclim.2015.06.005

200. Bahadur, A.V. and T. Tanner, 2014: Policy climates and climate policies: Analysing the politics of building urban climate change resilience. *Urban Climate*, **7**, 20–32. https://doi.org/10.1016/j.uclim.2013.08.004

201. Considine, M., J.M. Lewis, and D. Alexander, 2009: *Networks, Innovation and Public Policy: Politicians, Bureaucrats and the Pathways to Change inside Government*, 1st ed. Palgrave Macmillan, London, UK, 231 pp. https://doi.org/10.1057/9780230595040

202. Hamilton, M. and M. Lubell, 2018: Collaborative governance of climate change adaptation across spatial and institutional scales. *Policy Studies Journal*, **46** (2), 222–247. https://doi.org/10.1111/psj.12224

203. Martín, C. and S. McTarnaghan, 2018: Institutionalizing Urban Resilience: A Midterm Monitoring and Evaluation Report of 100 Resilient Cities. Urban Institute, Washington, DC. https://www.urban.org/research/publication/institutionalizing-urban-resilience

204. Moon, M.J. and D.F. Norris, 2005: Does managerial orientation matter? The adoption of reinventing government and e-government at the municipal level. *Information Systems Journal*, **15** (1), 43–60. https://doi.org/10.1111/j.1365-2575.2005.00185.x

205. Nelson, K.L. and J.H. Svara, 2010: Adaptation of models versus variations in form: Classifying structures of city government. *Urban Affairs Review*, **45** (4), 544–562. https://doi.org/10.1177/1078087409356349

206. Nelson, K.L. and J.H. Svara, 2012: Form of government still matters: Fostering innovation in U.S. municipal governments. *The American Review of Public Administration*, **42** (3), 257–281. https://doi.org/10.1177/0275074011399898

207. Nelson, K.L. and J.H. Svara, 2015: The roles of local government managers in theory and practice: A centennial perspective. *Public Administration Review*, **75** (1), 49–61. https://doi.org/10.1111/puar.12296

208. Nelson, K.L., C.H. Wood, and G.T. Gabris, 2011: Innovation management in local government: An empirical analysis of suburban municipalities. *International Journal of Organization Theory & Behavior*, **14** (3), 301–328. https://doi.org/10.1108/ijotb-14-03-2011-b001

209. Tanner, T., T. Mitchell, E. Polack, and B. Guenther, 2009: Urban governance for adaptation: Assessing climate change resilience in ten Asian cities. *IDS Working Papers*, **2009** (315), 01–47. https://doi.org/10.1111/j.2040-0209.2009.00315_2.x

210. Tyler, S. and M. Moench, 2012: A framework for urban climate resilience. *Climate and Development*, **4** (4), 311–326. https://doi.org/10.1080/17565529.2012.745389

211. Wallace, D. and R. Wallace, 2008: Urban systems during disasters: Factors for resilience. *Ecology and Society*, **13** (1), 18. https://doi.org/10.5751/es-02386-130118

212. Woodruff, S.C., S. Meerow, M. Stults, and C. Wilkins, 2022: Adaptation to resilience planning: Alternative pathways to prepare for climate change. *Journal of Planning Education and Research*, **42** (1), 64–75. https://doi.org/10.1177/0739456x18801057

213. Gourevitch, J.D., C. Kousky, Y. Liao, C. Nolte, A.B. Pollack, J.R. Porter, and J.A. Weill, 2023: Unpriced climate risk and the potential consequences of overvaluation in US housing markets. *Nature Climate Change*, **13** (3), 250–257. https://doi.org/10.1038/s41558-023-01594-8

214. Kousky, C. and K. French, 2023: Inclusive Insurance for Climate-Related Disasters: A Roadmap for the United States. Ceres, Boston, MA. https://www.ceres.org/resources/reports/report-inclusive-insurance-climate-related-disasters

215. Berke, P.R., W. Lyles, and G. Smith, 2014: Impacts of federal and state hazard mitigation policies on local land use policy. *Journal of Planning Education and Research*, **34** (1), 60–76. https://doi.org/10.1177/0739456x13517004

216. Bryan, T.K. and J.F. Wolf, 2010: Soft regionalism in action: Examining voluntary regional councils' structures, processes and programs. *Public Organization Review*, **10** (2), 99–115. https://doi.org/10.1007/s11115-009-0090-y

217. Chu, E.K., S. Hughes, and S.G. Mason, 2018: Ch. 18. Conclusion: Multilevel governance and climate change innovations in cities. In: *Climate Change in Cities: Innovations in Multi-Level Governance*. Hughes, S., E. Chu, and S. Mason, Eds. Springer, Cham, Switzerland, 361–378. https://doi.org/10.1007/978-3-319-65003-6_18

218. Cole, D.H., 2015: Advantages of a polycentric approach to climate change policy. *Nature Climate Change*, **5** (2), 114–118. https://doi.org/10.1038/nclimate2490

219. GAO, 2009: Climate Change Adaptation: Strategic Federal Planning Could Help Government Officials Make More Informed Decisions. GAO-10-113. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-10-113.pdf

220. Hsu, A. and R. Rauber, 2021: Diverse climate actors show limited coordination in a large-scale text analysis of strategy documents. *Communications Earth & Environment*, **2** (1), 30. https://doi.org/10.1038/s43247-021-00098-7

221. Landauer, M., S. Juhola, and J. Klein, 2019: The role of scale in integrating climate change adaptation and mitigation in cities. *Journal of Environmental Planning and Management*, **62** (5), 741–765. https://doi.org/10.1080/09640568.2018.1430022

222. Ostrom, E., 2010: Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change*, **20** (4), 550–557. https://doi.org/10.1016/j.gloenvcha.2010.07.004

223. Ostrom, E., 2012: Nested externalities and polycentric institutions: Must we wait for global solutions to climate change before taking actions at other scales? *Economic Theory*, **49** (2), 353–369. https://doi.org/10.1007/s00199-010-0558-6

224. Pendall, R., S. Rosenbloom, D.K. Levy, E. Oo, G. Knaap, J. Sartori, and A. Chakraborty, 2013: Can Federal Efforts Advance Federal and Local De-Siloing? UI No. 08752-000-00. Urban Institute, Washington, DC. https://www.urban.org/research/publication/can-federal-efforts-advance-federal-and-local-de-siloing-full-report

225. Davies, J.S., 2009: The limits of joined-up government: Towards a political analysis. *Public Administration*, **87** (1), 80–96. https://doi.org/10.1111/j.1467-9299.2008.01740.x

226. Fernandez, S. and H.G. Rainey, 2006: Managing successful organizational change in the public sector. *Public Administration Review*, **66** (2), 168–176. https://doi.org/10.1111/j.1540-6210.2006.00570.x

227. Franzel, J.M., 2008: Urban government innovation: Identifying current innovations and factors that contribute to their adoption. *Review of Policy Research*, **25** (3), 253–277. https://doi.org/10.1111/j.1541-1338.2008.00326.x

228. Fu, X., 2020: Measuring local sea-level rise adaptation and adaptive capacity: A national survey in the United States. *Cities*, **102**, 102717. https://doi.org/10.1016/j.cities.2020.102717

229. Kimble, D., J. Boex, and G. Kapitanova, 2012: Making Decentralization Work in Developing Countries: Transforming Local Government Entities into High-Performing Local Government Organizations. IDG Policy Brief. Urban Institute Center on International Development and Governance, 6 pp. https://www.urban.org/sites/default/files/publication/26271/412710-Making-Decentralization-Work-in-Developing-Countries-Transforming-Local-Government-Entities-into-High-Performing-Organizations.PDF

230. Krebs, T.B. and J.P. Pelissero, 2010: What influences city council adoption and support for reinventing government? Environmental or institutional factors? *Public Administration Review*, **70** (2), 258–267. https://doi.org/10.1111/j.1540-6210.2010.02132.x

231. Kwon, M., F.S. Berry, and R.C. Feiock, 2009: Understanding the adoption and timing of economic development strategies in US cities using innovation and institutional analysis. *Journal of Public Administration Research and Theory*, **19** (4), 967–988. https://doi.org/10.1093/jopart/mun026

232. Olazabal, M. and M. Ruiz De Gopegui, 2021: Adaptation planning in large cities is unlikely to be effective. *Landscape and Urban Planning*, **206**, 103974. https://doi.org/10.1016/j.landurbplan.2020.103974

233. Olazabal, M., M. Ruiz de Gopegui, E.L. Tompkins, K. Venner, and R. Smith, 2019: A cross-scale worldwide analysis of coastal adaptation planning. *Environmental Research Letters*, **14** (12), 124056. https://doi.org/10.1088/1748-9326/ab5532

234. Rosenbloom, D., J. Meadowcroft, and B. Cashore, 2019: Stability and climate policy? Harnessing insights on path dependence, policy feedback, and transition pathways. *Energy Research & Social Science*, **50**, 168–178. https://doi.org/10.1016/j.erss.2018.12.009

235. Stokes, L.C., 2020: *Short Circuiting Policy: Interest Groups and the Battle Over Clean Energy and Climate Policy in the American States*. Oxford University Press, New York. https://doi.org/10.1093/oso/9780190074258.001.0001

236. Ruppert, T. and E.L. Deady, 2017: Ch. 7. Climate change impacts on law and policy in Florida. In: *Florida's Climate: Changes, Variations, & Impacts*. Florida Climate Institute, 209–234. https://doi.org/10.17125/fci2017.ch07

237. Bushnell, J.B., S.P. Holland, J.E. Hughes, and C.R. Knittel, 2017: Strategic policy choice in state-level regulation: The EPA's clean power plan. *American Economic Journal: Economic Policy*, **9** (2), 57–90. https://doi.org/10.1257/pol.20150237

238. Vella, K., W.H. Butler, N. Sipe, T. Chapin, and J. Murley, 2016: Voluntary collaboration for adaptive governance: The southeast Florida regional climate change compact. *Journal of Planning Education and Research*, **36** (3), 363–376. https://doi.org/10.1177/0739456x16659700

239. Fastiggi, M., S. Meerow, and T.R. Miller, 2021: Governing urban resilience: Organisational structures and coordination strategies in 20 North American city governments. *Urban Studies*, **58** (6), 1262–1285. https://doi.org/10.1177/0042098020907277

240. McTarnaghan, S., J. Morales-Burnett, and R. Marx, 2022: Urban Resilience: From Global Vision to Local Practice. Urban Institute. https://www.urban.org/research/publication/urban-resilience-global-vision-local-practice

241. IPCC, 2023: Summary for policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Lee, H. and J. Romero, Eds. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 1-34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

242. Reed, P.M., A. Hadjimichael, R.H. Moss, C. Brelsford, C.D. Burleyson, S. Cohen, A. Dyreson, D.F. Gold, R.S. Gupta, K. Keller, M. Konar, E. Monier, J. Morris, V. Srikrishnan, N. Voisin, and J. Yoon, 2022: Multisector dynamics: Advancing the science of complex adaptive human-Earth systems. *Earth's Future*, **10** (3), e2021EF002621. https://doi.org/10.1029/2021ef002621

243. Carter, T.R., M. Benzie, E. Campiglio, H. Carlsen, S. Fronzek, M. Hildén, C.P.O. Reyer, and C. West, 2021: A conceptual framework for cross-border impacts of climate change. *Global Environmental Change*, **69**, 102307. https://doi.org/10.1016/j.gloenvcha.2021.102307

244. Challinor, A.J., W.N. Adger, T.G. Benton, D. Conway, M. Joshi, and D. Frame, 2018: Transmission of climate risks across sectors and borders. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376** (2121), 20170301. https://doi.org/10.1098/rsta.2017.0301

245. Gill, J.C. and B.D. Malamud, 2014: Reviewing and visualizing the interactions of natural hazards. *Reviews of Geophysics*, **52** (4), 680–722. https://doi.org/10.1002/2013rg000445

246. Leonard, M., S. Westra, A. Phatak, M. Lambert, B. van den Hurk, K. McInnes, J. Risbey, S. Schuster, D. Jakob, and M. Stafford-Smith, 2014: A compound event framework for understanding extreme impacts. *WIREs Climate Change*, **5** (1), 113–128. https://doi.org/10.1002/wcc.252

247. Pescaroli, G. and D. Alexander, 2018: Understanding compound, interconnected, interacting, and cascading risks: A holistic framework. *Risk Analysis*, **38** (11), 2245–2257. https://doi.org/10.1111/risa.13128

248. Raymond, C., R.M. Horton, J. Zscheischler, O. Martius, A. AghaKouchak, J. Balch, S.G. Bowen, S.J. Camargo, J. Hess, K. Kornhuber, M. Oppenheimer, A.C. Ruane, T. Wahl, and K. White, 2020: Understanding and managing connected extreme events. *Nature Climate Change*, **10** (7), 611–621. https://doi.org/10.1038/s41558-020-0790-4

249. Zscheischler, J., O. Martius, S. Westra, E. Bevacqua, C. Raymond, R.M. Horton, B. van den Hurk, A. AghaKouchak, A. Jézéquel, M.D. Mahecha, D. Maraun, A.M. Ramos, N.N. Ridder, W. Thiery, and E. Vignotto, 2020: A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, **1** (7), 333–347. https://doi.org/10.1038/s43017-020-0060-z

250. Callaghan, M., C.-F. Schleussner, S. Nath, Q. Lejeune, T.R. Knutson, M. Reichstein, G. Hansen, E. Theokritoff, M. Andrijevic, R.J. Brecha, M. Hegarty, C. Jones, K. Lee, A. Lucas, N. van Maanen, I. Menke, P. Pfleiderer, B. Yesil, and J.C. Minx, 2021: Machine-learning-based evidence and attribution mapping of 100,000 climate impact studies. *Nature Climate Change*, **11** (11), 966–972. https://doi.org/10.1038/s41558-021-01168-6

251. Aune, K.T., D. Gesch, and G.S. Smith, 2020: A spatial analysis of climate gentrification in Orleans Parish, Louisiana post-Hurricane Katrina. *Environmental Research*, **185**, 109384. https://doi.org/10.1016/j.envres.2020.109384

252. Gould, K.A. and T.L. Lewis, 2018: From green gentrification to resilience gentrification: An example from Brooklyn. *City & Community*, **17** (1), 12–15. https://doi.org/10.1111/cico.12283

253. Immergluck, D. and T. Balan, 2018: Sustainable for whom? Green urban development, environmental gentrification, and the Atlanta Beltline. *Urban Geography*, **39** (4), 546–562. https://doi.org/10.1080/02723638.2017.1360041

254. Laska, S., Ed. 2020: *Louisiana's Response to Extreme Weather: A Coastal State's Adaptation Challenges and Successes*. Springer, Cham, Switzerland, 361 pp. https://doi.org/10.1007/978-3-030-27205-0

255. Marino, E., 2015: *Fierce Climate, Sacred Ground: An Ethnography of Climate Change in Shishmaref, Alaska*. University of Alaska Press, Fairbanks, AK, 122 pp. https://upcolorado.com/university-of-alaska-press/item/5674-fierce-climate-sacred-ground

256. Marino, E., 2018: Adaptation privilege and voluntary buyouts: Perspectives on ethnocentrism in sea level rise relocation and retreat policies in the US. *Global Environmental Change*, **49**, 10–13. https://doi.org/10.1016/j.gloenvcha.2018.01.002

257. Cha, J.M., 2020: A just transition for whom? Politics, contestation, and social identity in the disruption of coal in the Powder River Basin. *Energy Research and Social Science*, **69**, 101657. https://doi.org/10.1016/j.erss.2020.101657

258. Rice, J.L., D.A. Cohen, J. Long, and J.R. Jurjevich, 2020: Contradictions of the climate-friendly city: New perspectives on eco-gentrification and housing justice. *International Journal of Urban and Regional Research*, **44** (1), 145–165. https://doi.org/10.1111/1468-2427.12740

259. Moon, K. and D. Blackman, 2014: A guide to understanding social science research for natural scientists. *Conservation Biology*, **28** (5), 1167–1177. https://doi.org/10.1111/cobi.12326

260. Treuer, G., E. Koebele, A. Deslatte, K. Ernst, M. Garcia, and K. Manago, 2017: A narrative method for analyzing transitions in urban water management: The case of the Miami-Dade water and sewer department. *Water Resources Research*, **53** (1), 891–908. https://doi.org/10.1002/2016wr019658

261. Kim, S.K., 2019: The Economic Effects of Climate Change Adaptation Measures: Evidence from Miami-Dade County and New York City. Joint Center for Housing Studies of Harvard University, Cambridge, MA. https://www.jchs.harvard.edu/research-areas/working-papers/economic-effects-climate-change-adaptation-measures-evidence-miami

262. Solecki, W., G.C. Delgado Ramos, D. Roberts, C. Rosenzweig, and B. Walsh, 2021: Accelerating climate research and action in cities through advanced science-policy-practice partnerships. *Npj Urban Sustainability*, **1** (1), 3. https://doi.org/10.1038/s42949-021-00015-z

263. Lubell, M. and M. Robbins, 2022: Adapting to sea-level rise: Centralization or decentralization in polycentric governance systems? *Policy Studies Journal*, **50** (1), 143–175. https://doi.org/10.1111/psj.12430

264. Djenontin, I.N.S. and A.M. Meadow, 2018: The art of co-production of knowledge in environmental sciences and management: Lessons from international practice. *Environmental Management*, **61** (6), 885–903. https://doi.org/10.1007/s00267-018-1028-3

265. Araos, M., K. Jagannathan, R. Shukla, I. Ajibade, E. Coughlan de Perez, K. Davis, J.D. Ford, E.K. Galappaththi, C. Grady, A.J. Hudson, E.T. Joe, C.J. Kirchhoff, A. Lesnikowski, G.N. Alverio, M. Nielsen, B. Orlove, B. Pentz, D. Reckien, A.R. Siders, N. Ulibarri, M. van Aalst, T.Z. Abu, T. Agrawal, L. Berrang-Ford, R.B. Kerr, S. Coggins, M. Garschagen, A. Harden, K.J. Mach, A.M. Nunbogu, P. Spandan, S. Templeman, and L.L. Turek-Hankins, 2021: Equity in human adaptation-related responses: A systematic global review. *One Earth*, **4** (10), 1454–1467. https://doi.org/10.1016/j.oneear.2021.09.001

266. Arnott, J.C. and M.C. Lemos, 2021: Understanding knowledge use for sustainability. *Environmental Science & Policy*, **120**, 222–230. https://doi.org/10.1016/j.envsci.2021.02.016

267. Karcher, D.B., C. Cvitanovic, R.M. Colvin, I.E. van Putten, and M.S. Reed, 2021: Is this what success looks like? Mismatches between the aims, claims, and evidence used to demonstrate impact from knowledge exchange processes at the interface of environmental science and policy. *Environmental Science & Policy*, **125**, 202–218. https://doi.org/10.1016/j.envsci.2021.08.012

268. Owen, G., 2021: Evaluating socially engaged climate research: Scientists' visions of a climate resilient U.S. southwest. *Research Evaluation*, **30** (1), 26–38. https://doi.org/10.1093/reseval/rvaa028

269. Jagannathan, K., G. Emmanuel, J. Arnott, K.J. Mach, A. Bamzai-Dodson, K. Goodrich, R. Meyer, M. Neff, K.D. Sjostrom, K.M.F. Timm, E. Turnhout, G. Wong-Parodi, A.T. Bednarek, A. Meadow, A. Dewulf, C.J. Kirchhoff, R.H. Moss, L. Nichols, E. Oldach, M.C. Lemos, and N. Klenk, 2023: A research agenda for the science of actionable knowledge: Drawing from a review of the most misguided to the most enlightened claims in the science-policy interface literature. *Environmental Science & Policy*, **144**, 174–186. https://doi.org/10.1016/j.envsci.2023.03.004

270. Turnhout, E., T. Metze, C. Wyborn, N. Klenk, and E. Louder, 2020: The politics of co-production: Participation, power, and transformation. *Current Opinion in Environmental Sustainability*, **42**, 15–21. https://doi.org/10.1016/j.cosust.2019.11.009

Fifth National Climate Assessment: Chapter 19

# Economics

# Chapter 19. Economics

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# Introduction

The climate is a national asset that enables and contributes value to diverse economic activities across the United States, from agriculture, finance, and tourism to healthcare, education, and real estate. Changes in the climate are expected to impose substantial new costs to the US economy and adversely affect the economic opportunities of most Americans. Climate change, and the policies adopted in response to it, are also expected to alter both the domestic US economy and the global economy in which the US competes. These economic consequences are projected to be highly uneven across US regions, industries, and communities.

Climate change has *direct* and *indirect* effects on economic outcomes. Direct impacts affect individuals and other basic components of the economy (e.g., buildings, crops). These direct impacts may in turn cause secondary indirect impacts resulting from markets, governments, and other institutions adjusting to direct changes. For example, changes in rainfall patterns and sea level rise put existing homes at risk of flooding, a direct effect. Elevated flood risk in turn causes indirect effects, including lowering home prices, increasing risks to mortgage-providing businesses, and altering the cost of flood insurance provided by the Federal Government.

This chapter assesses the effects of climate change on US markets, budgets, and the economic opportunities of households, businesses, and institutions. This chapter does not assess the economics of climate change mitigation and technological solutions, which are covered elsewhere (e.g., KMs 31.1, 31.2, 17.3).[1,2]

## Key Message 19.1

## Climate Change Affects the Economy Directly

Climate change directly impacts the economy through increases in temperature, rising sea levels, and more frequent and intense weather-related extreme events (e.g., wildfires, floods, hurricanes, droughts), which are estimated to generate substantial and increasing economic costs in many sectors (*likely*, *high confidence*). These impacts are projected to be distributed unequally, affecting certain regions, industries, and socioeconomic groups more than others (*very likely*, *high confidence*). Adaptation can attenuate some impacts by reducing vulnerability to climate change, but adaptation strategies vary in their effectiveness and costs (*medium confidence*).

### *Observed Direct Impacts*

Direct economic impacts of climate change have been observed in many economic sectors (e.g., Table 19.1a). For example, more frequent extreme events and higher temperatures lead to direct economic losses via infrastructure damage,[3] worker injuries,[4] and crop loss.[5]

Climate change also directly affects valuable resources that are not traded in markets, such as human health and ecosystems. These *nonmarket impacts* are sometimes difficult to quantify but are nonetheless economically important and represent a substantial fraction of the economic burden of climate change on Americans (Table 19.1c). For example, rising temperatures, extreme weather, wildfires, vector-borne diseases, food insecurity, and knowledge of the threat of climate change itself have all been linked to declines in Americans' physical and mental health.[6,7,8,9,10] Additionally, changes in ecosystems caused by climate change have impacted food production, water resources, forestry, human health, real estate values, recreation, and tourism (KM 6.1, 7.3).[11,12,13]

## Projected Direct Impacts

While some economic impacts of climate change are already being felt, the impacts of future changes are projected to be more significant and apparent across more sectors of the economy (e.g., Figure 19.1 and Table 19.1b). With every additional degree of warming, the United States is expected to see increasingly adverse consequences. For example, warming global temperatures by 2°F is projected to cause more than twice the economic harm induced by 1°F of warming.[14,15]

As climate change advances, economic risks are projected to grow over time. For example, weather-related disasters currently generate at least $150 billion per year (in 2022 dollars) in direct damages to the US,[16] a cost that is projected to increase due to climate change in the near term.[17,18,19] Over the next few decades, climate change is projected to cause ecosystem disruptions,[20] water stress,[21] and agricultural losses.[22,23,24,25,26,27,28] Over the coming century, the country faces relocation costs and damage to property and infrastructure due to coastal flooding,[29] major adverse impacts on ecosystem services,[30] substantial and unequal health costs,[7] large negative impacts on economic production,[31] and a restructured investment landscape.[32]

While many sectors are impacted by changing weather conditions, agriculture is also directly impacted by higher carbon dioxide ($CO_2$) levels, because plants use $CO_2$ during photosynthesis. The effect of a $CO_2$-enriched environment is not well understood and depends on crop types and the availability of water and soil nutrients.[33] In some cases, $CO_2$ enrichment increases biomass but causes the nutritional value of agricultural output to decline.[34] Overall, the risks climate change poses to agriculture are expected to outweigh any potential benefits due to $CO_2$ fertilization or other factors such as longer growing seasons and expanded crop ranges (KMs 11.1, 21.1, 22.4, 23.3, 24.1, 26.2).

Projected economic impacts are not certain, as they depend on factors that cannot be known precisely. The largest source of uncertainty in projected impacts is the unknown trajectory of future greenhouse gas emissions,[35] which depend on mitigation policy, economic development, population growth, and other factors (KM 2.3). The uncertainty caused by climate change is itself an economic burden, since individuals are generally risk averse (Box 19.1).[36,37]

Economic impacts of climate change will vary by location due to different hazards, regional climate change patterns, and historical climate (Figure 19.1; KM 3.4). For example, locations that are hot today are generally projected to suffer greater damage because warming from 100°F to 105°F has a larger effect on human health, energy use, labor supply, and crop yields than warming from 60°F to 65°F.[7,26,38,39] Population density also influences the local economic impacts of climate change, since dense populations exacerbate urban heat islands and groundwater drawdown but improve the cost effectiveness of some public adaptation projects, such as seawalls.[40,41]

Cold regions may benefit from low levels of warming while temperate and hot regions are generally harmed.[15] Within most sectors that have been studied, more Americans are harmed than are helped by climate change (Figure 19.1b).[3,7,42,43,44,45,46,47] Estimates of nationwide impacts indicate a net loss in the economic well-being of American society (Figure 19.1c; e.g., Hsiang et al. 2017;[15] Rode et al. 2021,[46] 2022;[45] Hultgren et al. 2022;[43] Carleton et al. 2022;[7] Martinich and Crimmins 2019[44]).

## Table 19.1. Example US Economic Impacts of Climate Extremes and Climate Change

Shown are observed and projected impacts of a sample of climate extremes and climate changes on US economic outcomes, as they are estimated in the context of particular studies. Note that only a subset of climate drivers may have been assessed in each study. Section (**a**) shows impacts on current economic outcomes. Section (**b**) shows projected future impacts. Section (**c**) highlights examples of important but unquantified impacts. All impacts are for the US and in 2022 dollars unless otherwise noted. GDP stands for gross domestic product, a standard measure of total domestic economic production. These estimates are illustrative and not comprehensive. See metadata for table credits.

Key: * indicates an intermediate scenario (e.g., RCP4.5); ** indicates a high scenario (e.g., RCP6.0); *** indicates a very high scenario (e.g., RCP8.5); † indicates 3% discount rate.

### a) Sample Current Impact Estimates of Climate Hazards on US Economic Outcomes

| Sector | Impact Type | Climate Hazard | Economic Estimate |
|---|---|---|---|
| Government, Agriculture | Crop insurance payouts | Temperature increases | +19% of federally subsidized payouts[48] |
| Agriculture | Rural outmigration | Warming-linked crop failure | +0.17% for 1% crop yield reduction[49] |
| Business | Commercial mortgage delinquency | Hurricane | +28% per 10% damage increase[50] |
| Business | GDP growthW | Hurricane | −0.45 percentage point annual growth rate per hurricane[51] |
| Government | Municipal borrowing costs | Sea level rise | +23.4 basis points annualized bond issuance cost per 1% additional GDP loss due to sea level rise[52] |
| Government | Municipal budgets | Wildfire | +25 percentage point increase in likelihood of budget deficit[53] |
| Government | Social safety net transfers | Hurricane | +$975–$1,440 per capita[54] |
| Households | Housing prices | Flooding | −4.6% (in 100-year floodplain)[55] |
| Households | Student learning | Temperature increases | 1% decrease in test scores per 1°F hotter school year (no adaptation)[56] |
| Infrastructure | Property values | Sea level rise | −14.7% (1-foot rise)[57] |
| Agriculture, Infrastructure | Damage to structures and crops | Flooding | +$235 billion per year[58] |
| Labor | Earnings | Wildfire smoke | −$144 billion per year[59] |
| Labor | Work injuries | Heat (≥85°F day) | +5%–15% per hot day[4] |

| Sector | Impact Type | Climate Hazard | Economic Estimate |
|---|---|---|---|
| | Wages as adult | Heat (≥90°F day) | −0.1% per hot day in utero[60] |
| | Emergency department costs | Heat (≥80°F day) | +$10,600 per 100,000 people aged 80+[61] |
| | Mortality | Heat (≥90°F day) | +0.9 deaths per 100,000 people[62] |
| | Alaska Native village relocation | Warming-linked erosion | $28–$280 million costs per village (adaptation only)[63] |

**b) Sample Future Impact Estimates of Projected Climate Hazards on US Economic Outcomes**

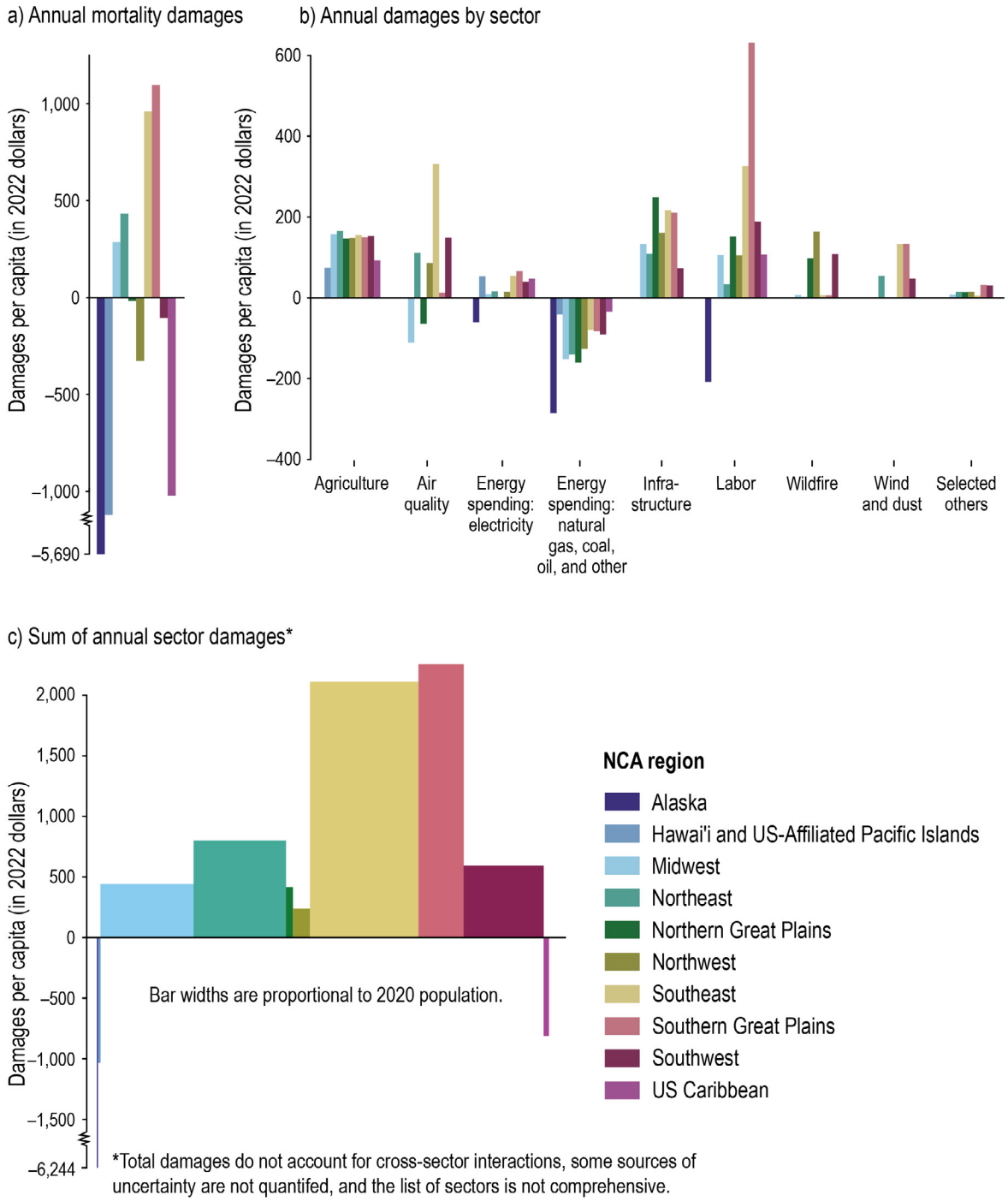
| Sector | Impact Type | Climate Hazard | Economic Estimate |
|---|---|---|---|
| | Agricultural yields (maize, soybeans, winter wheat, spring wheat, cotton, and sorghum) | Temperature, moisture changes | 12%–29%* decrease (2050–2100)[21]<br>20%–48%*** decrease (2050–2100)[21] |
| | Agricultural yields (maize, soybeans, and cotton) | Temperature, precipitation changes | 30%–46%* decrease (2070–2099)[26]<br>63%–82%*** decrease (2070–2099)[26] |
| | Aggregate multisector impact | Temperature increases | −0.1%–1.7% GDP loss*[15]<br>1.5%–5.6% GDP loss***[15] |
| | Airline network disruption | Temperature increases | +16%–50% recovery costs (2035, global)***[64] |
| | GDP growth | Temperature increases | −0.13 percentage points per year per 1°F warming[31] |
| | Income | Temperature increases | −19.6% global GDP per capita (3°C [5.4°F] of warming)[31] |
| | Income | Hurricanes | 29% GDP loss**†[65] |
| | Federal disaster response | Hurricanes | +$5.2 billion* (2050 annual expenditures)[66]<br>+$36 billion*** (2050 annual expenditures)[66] |
| | National Flood Insurance Program | Flooding | +$3.9 billion annual losses (2050)*[66]<br>+$5.1 billion annual losses (2100)*[66] |
| | Property tax revenue | Sea level rise | −1.4% (3-foot rise)[67] |
| | Public services | Temperature increases | +1.45% costs (2050)***[68] |
| | Coastal damages | Sea level rise | +$550 billion (optimal adaptation)***[40]<br>+$2.6 trillion (no adaptation)***[40] |

| Sector | Impact Type | Climate Hazard | Economic Estimate |
|---|---|---|---|
| | Electricity outages | Temperature, precipitation changes | +$2.3–$6.8 trillion consumer costs***[69] |
| | Flooding costs | Flooding | +61% annual losses (2050)*[70] |
| | Railroad disruption | Temperature increases | +$30–$55 billion* costs from network delays[71]<br>+$43–$73 billion*** costs from network delays[71] |
| | Road degradation | Temperature, precipitation changes | +$116 billion*** costs†[29] |
| | Urban drainage degradation | Temperature, precipitation changes | +$29 billion*** costs†[29] |
| | Alaska Native village relocation and protection costs | Flooding, erosion, permafrost subsidence | +$3.9 billion over 50 years (adaptation only)[72] |
| | Migration from Mexico to US | Temperature, precipitation changes | +0.7 million* migrants[73,252,253]<br>+3.2 million*** migrants[73,252,253] |
| | Mortality (all causes) | Wildfire | +9–20 deaths per 100,000 people ≥65 years old (for 50% increase in smoke)[74] |
| | Suicides | Temperature increases | +5,600–26,000 deaths by 2050***[6] |
| | Recreation (boating, cycling, hiking, running, water sports) | Temperature, precipitation, snowfall changes | $11.6 billion (annual welfare gains 2050–2100)***[75] |
| | Recreation (fishing, hunting, skiing, ice skating, snowboarding) | Temperature, precipitation, snowfall changes | $4.6 billion (annual welfare losses 2050–2100)***[75] |

**c) Sample Impacts That Are Difficult to Quantify in Economic Terms**

| Sector | Impact type | Climate hazard | Economic estimate |
|---|---|---|---|
| | Happiness | ? | ? |
| | Preservation of national landmarks | ? | ? |
| | Loss of cultural heritage and resources | ? | ? |
| | Subsistence activities | ? | ? |

## Example Projected US Economic Damages for 3°F of Global Warming




**Projected economic impacts of climate change vary by sector and region, with aggregate impacts resulting in net damages nationally.**

**Figure 19.1.** Shown are estimates of annual economic damages in each National Climate Assessment region for several sectors in a scenario where global surface temperature increases 3°F (1.67°C). Positive damages indicate harm and negative damages indicate benefits. Panels (**a**) and (**b**) show per capita damages by region broken down by sector. Panel (**c**) shows summed per capita damages across sectors by region, with bar width corresponding to 2020 population. Most regions experience positive damages in most sectors. In aggregate, nearly all regions and the vast majority of the American population are projected to experience economic harm from climate change. Note that these damages do not account for cross-sector interactions, some sources of uncertainty are not quantified, and the list of sectors is not comprehensive. See Table 19.1 for further examples of sectors impacted by climate change. Citations for each study underpinning these results are available in the figure metadata. Figure credit: See figure metadata for contributors.

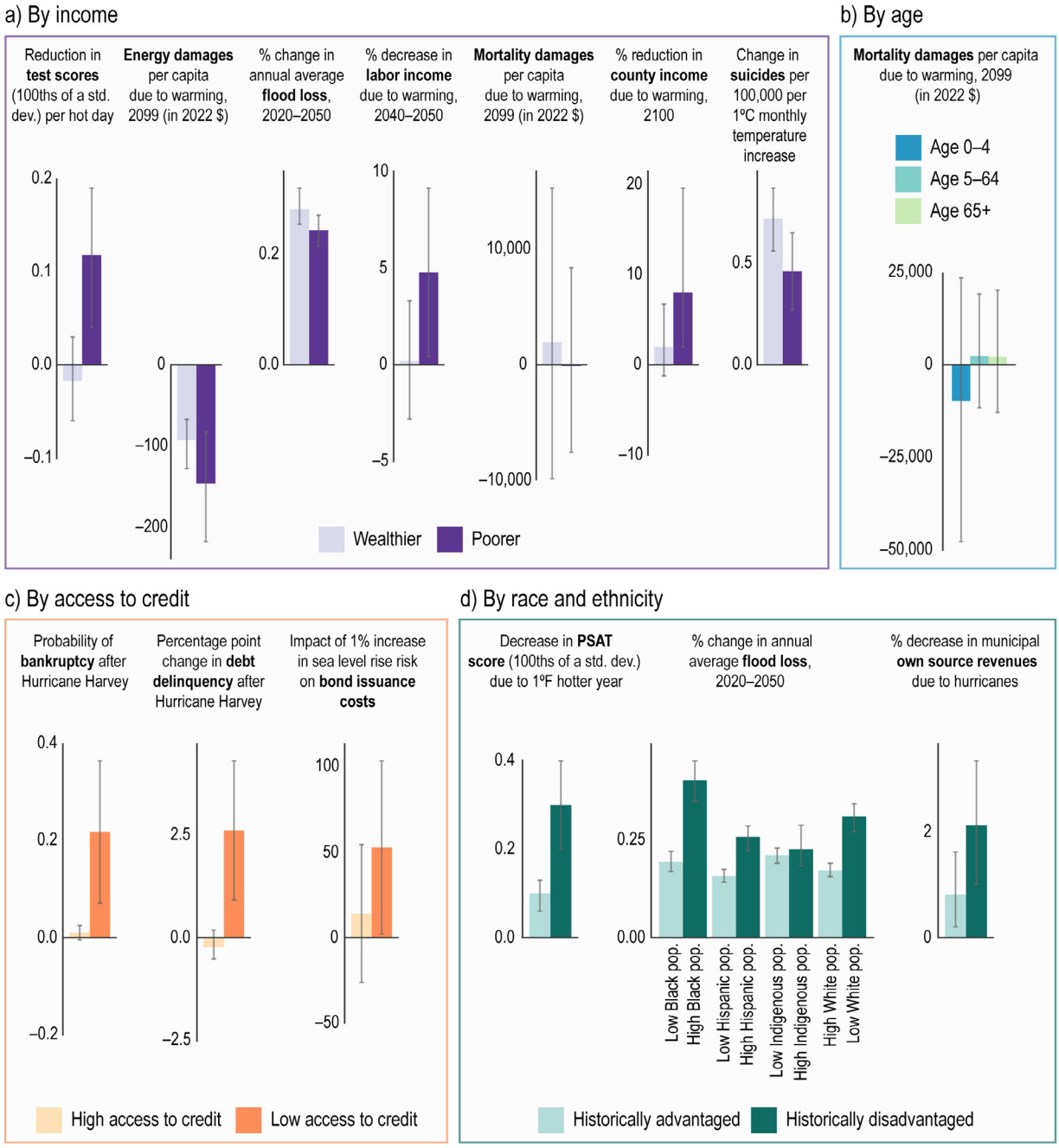
## Adaptation

Adaptation to climate change can reduce some economic impacts.[38,40] For example, adaptation is expected to reduce storm-related climate damages by approximately one-third.[76] In some sectors, however, there is limited scope for adaptation (Ch. 31).[77,78] Natural and human systems may not be able to adapt quickly, so gradual warming is expected to be less harmful than rapid warming.[40] Adaptation can occur when populations have access to technologies or opportunities that lower their vulnerability to harmful conditions at sufficiently low cost.[41,79] Around 1% of the US capital stock is estimated to be adaptation capital.[76] Some adaptation strategies require new investments, expenditures, or consumption changes that offset or outweigh their benefits.[7,80,81] These adaptation costs may be large enough to prevent existing technologies from being utilized, particularly among low-income communities.[41,46] Adaptation may also face political difficulties, require behavior changes that populations are reticent to adopt,[82] or depend on technologies that do not yet exist or are in their infancy.[83] These factors make the projected timing and effectiveness of adaptations uncertain.[77]

## Economic Vulnerability and Inequality

Economic damages from climate change are distributed unevenly across American society, often amplifying existing inequalities (Figure 19.2). Certain communities and individuals are more sensitive to climate impacts, are more exposed to climate hazards, or lack the resources to adapt to climate changes and recover from damages caused by natural hazards.[18,46,76,84,85,86,87,88,89,90,91,92] For example, people with preexisting health conditions and older adults may be relatively more sensitive to heat or air quality impacts such as wildfire smoke (KMs 14.3, 15.2).[4,93] Families living below the poverty line often live where climatic changes are expected to be the most economically damaging, like the already-hot Southeast (KMs 22.3, 22.4).[15] Climate-driven relocations of Alaska Native communities have already occurred where warming is happening fastest (KMs 16.1, 29.3, 29.5).[94,95] Climatic stressors have also been shown to increase racial segregation,[96] gentrification,[97] income inequality,[98] and low-income communities' reliance on social safety net programs and credit systems.[54,85,99] Climate change also introduces fiscal risks (Figure 19.3; KM 19.2) that may threaten programs vulnerable communities rely on.[100] Broad research gaps remain about unequal climate change impacts across demographics, health status, and socioeconomic background.

## Climate Damages by Income, Age, Access to Credit, and Race and Ethnicity




**The effects of weather and climate change are often experienced differently by populations according to income, age, access to credit, and race and ethnicity.**

**Figure 19.2.** Each bar plot summarizes findings from a single study with impact estimates for different groups. Whiskers represent 95% confidence intervals, with the exception of the whiskers on the multisector aggregate panel, which are 90% confidence intervals. (**a**) The first set of estimates show unequal impacts by wealth. (**b**) The second set of estimates show unequal impacts across age groups. (**c**) The third set of estimates show unequal impacts by credit access. (**d**) The fourth set of estimates show unequal impacts by historically advantaged and disadvantaged populations. The citations for each study are available in the metadata. Many of these estimates are uncertain, and differences between groups are often not statistically significant. Further examples of unequal climate impacts within National Climate Assessment regions are available in Figure 22.4 and Key Message 20.1. Figure credit: See figure metadata for contributors.

## Key Message 19.2

## Markets and Budgets Respond to Climate Change

Markets are responding to current and anticipated climate changes, and stronger market responses are expected as climate change progresses (*medium confidence*). Climate risks are projected to change asset values as markets and prices adjust to reflect economic conditions that result from climate change (*very likely*, *high confidence*). New costs and challenges will emerge in insurance systems and public budgets that were not originally designed to respond to climate change (*high confidence*). Trade and economic growth are projected to be impacted by climate change directly and through policy responses to climate change (*likely*, *medium confidence*).

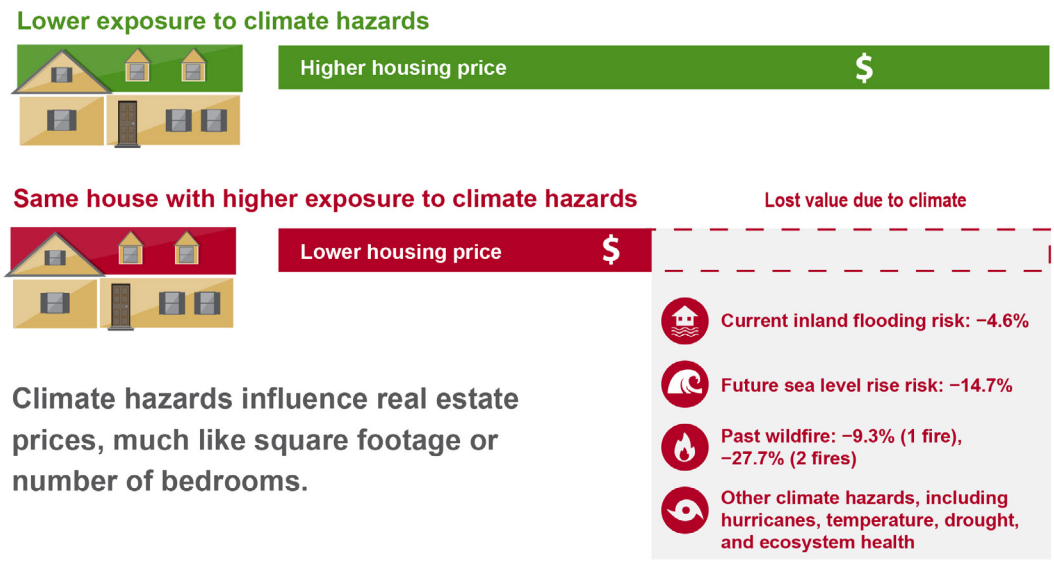
### *Markets*

Markets aggregate information from many individuals and firms, generating system-level outcomes (e.g., market prices). Prices in well-functioning markets will reflect assets' exposure to future climate risks and expected adaptation costs. For example, anticipation of future flood risk has begun to reduce the prices of vulnerable properties (Figure 19.3).[57,101] But there are barriers that sometimes prevent market prices from adjusting to reflect climate risks,[102] such as inaccurate information or incomplete understanding of relevant climate risks.[103,104,105,106] Increasing awareness of climate change is expected to tighten the link between asset prices and climate risks in financial markets and may lead to abrupt price adjustments.[52,57,107,108,109]

Changes in prices due to climate change can have different impacts on producers and consumers. For example, higher temperatures around the globe are expected to lead to a reduction in global production of corn, wheat, rice, and soybeans.[43] This reduction in supply is expected to increase crop prices.[110] In some cases, these higher prices could financially offset the reduction in yields for farmers, but US consumers would face the burden of the higher food prices.[111]

Insurance markets are important for financial resilience to changing climate extremes, but insurance coverage is costly, and prices may exceed what households and businesses are willing or able to pay.[112] As the risk of climate extremes grows, private insurers are expected to abandon high-hazard areas, as is occurring in some wildfire- and hurricane-prone locations.[113] Uninsured consumers face greater financial distress post-disaster,[114] and public-sector insurance programs, such as crop insurance and the National Flood Insurance Program, see increasing demand when private insurance markets contract. To account for the growing risks, fiscal costs of public insurance programs will rise.[66,115]

Stock and bond market prices generally reflect anticipated climate risks,[116] but pricing can be incomplete or distorted.[102,117] Anticipated policies to curb emissions can impact stock prices of emissions-intensive companies,[108,118] and long-term bonds issued by municipalities exposed to future climate risks tend to have lower prices.[52,119] In the absence of strong global mitigation policies, some forward-looking financial institutions are preemptively responding to potential impacts by restructuring portfolios.[120,121]




**Exposure to climate hazards has a negative effect on real estate values.**

**Figure 19.3.** Exposure to past climate events and to present and future climate risks affects the values of otherwise identical properties. The market price for real estate is reduced when the property is exposed to adverse climate extremes or risks. Percentages shown are example estimates from studies. Homes located in the present-day 100-year floodplain cost 4.6% less than comparable homes outside the floodplain;[55] homes projected to be inundated by 1 foot of sea level rise cost 14.7% less;[57] and homes located near one recent wildfire cost 9.3% less, while those located near two recent wildfires cost 27.7% less.[122] Note that these are examples from specific studies, some of which are not nationally representative. Other climate hazards including hurricanes,[123] droughts,[124] temperature,[125] and ecosystem health,[126] among others, also affect real estate prices. Figure credit: See figure metadata for contributors.

## *Public Budgets, Healthcare, and Infrastructure*

Climate change will affect public budgets at all levels of government through changes in revenues, spending, and borrowing costs (Figure 19.4).[127,128,129] For example, sea level rise, wildfires, and hurricanes can decrease incomes[65,130] and housing values (Figure 19.3),[109,131] and thus tax revenues,[100] while simultaneously increasing public expenditures for healthcare, income support,[54] disaster assistance,[132] and defense spending.[133] This combination of declining revenue and increasing expenditures increases municipal borrowing costs.[52,53,100,119]

Climate change is expected to further increase the costs of public programs, such as crop insurance subsidies,[48,115] wildfire suppression,[66,134,135] endangered species protection,[136] and healthcare provision.[68,137,138] Given these demands, achieving sustainable public budgets in a changing climate is expected to require additional revenues or other expenditure reductions.[68,128]

US healthcare is provided by public systems and private markets, both of which will be impacted by climate change. Extreme weather events, such as hurricanes, damage healthcare facilities and impede medical care delivery[139,140,141] and create competition for healthcare services.[142] The direct health impacts of climate change (e.g., Ch. 15; Limaye et al. 2019[143]) are expected to generate higher medical costs, raising health insurance premiums, out-of-pocket spending, and expenditures on prevention efforts.[7,144,145]

Essential infrastructure, such as water, energy, communication, and transportation systems, will increasingly be compromised by the compounding effects of climate change impacts (Chs. 4, 5, 12, 13; Focus on Compound Events). Degradation or disruption of these assets, many of which are publicly owned, can have substantial repercussions on other sectors and the well-being of households (Table 19.1).

## Migration, Trade, and Growth

Future climate changes are expected to affect migration patterns, although how these shifts will occur is uncertain. Historical events that have shaped migrations include extended droughts, which drove rural populations toward urban centers,[124] and hurricanes, which have had persistent impacts on where people live.[146,147,148] Projections of increased flood risks due to sea level rise (KM 2.2) are expected to displace substantial populations.[149,150,151] Climate-driven economic changes abroad, including reductions in crop yields, are expected to continue increasing the rate of immigration to the United States.[73,152]

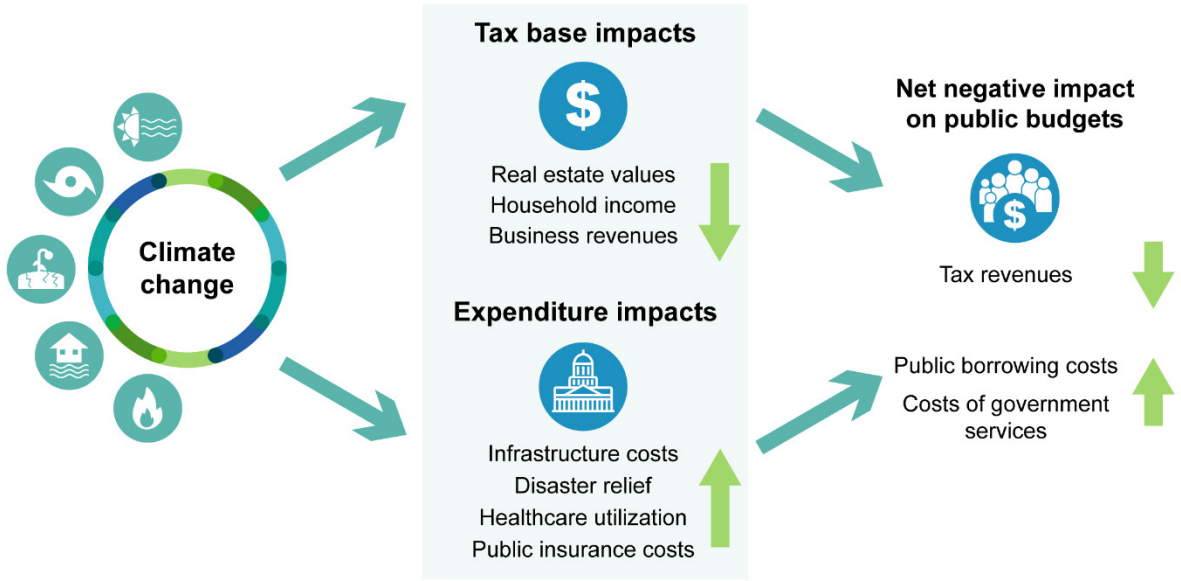
Global supply chains can transfer, amplify, or reduce the direct impacts of climate change (Focus on Risks to Supply Chains). Climatic events in other countries impact trade with the United States,[153] which in turn affects domestic markets (Ch. 17).[154] Climate impacts that affect multiple countries simultaneously amplify costs due to interacting disruptions and linked trade.[155] However, geographic diversification of supply chains would allow for businesses to flexibly adjust supplies to partially reduce their exposure to climate-associated risks.[156]

High annual temperatures and tropical cyclones are associated with lower growth in GDP,[31,65,157,158] with responses from multiple industries contributing to this overall effect. For each 1°F increase in global average surface temperature, annual US GDP growth is projected to slow roughly 0.13 percentage points,[31,157,158] with larger effects for larger temperature changes. These changes in growth rates can in turn affect stock market prices and interest rates.[159,160]

## Innovation

Economic impacts of climate change will motivate some investments in innovations aimed at reducing or limiting climate damages. For example, development of low-cost air-conditioning[38] and arid-tolerant crop varieties reduced the impact of historical climate conditions.[161] Future innovations may reduce costs or result in new adaptation technologies. However, some adaptation challenges have proven difficult to overcome,[162] and novel adaptive technologies are sometimes costly, often limiting their accessibility to high-income communities.[46] Nonetheless, strategic investments in key adaptation technologies have the potential to generate large social and private returns.

## Fiscal Risks of Climate Change




**Climate change puts pressure on public budgets.**

**Figure 19.4.** Climate change increases demand for government services while also reducing governments' ability to fund those services, creating new risks for the fiscal sustainability of government budgets at local, state, and federal levels. Tax revenues may fall due to decreased real estate values, household income, and business revenues.[53,100,163] Meanwhile, expenditures on infrastructure,[164] disaster relief,[132] healthcare,[54,68] and public insurance[135] are expected to increase. Together, this fiscal risk increases the cost to government for borrowing funds (e.g., the sale of bonds) by reducing the rating of public debt, which in turn further harms the ability of governments to fund services. Figure credit: See figure metadata for contributors.

## Box 19.1. Economic Decision-Making Under Uncertainty

Economists use economic and financial models to understand the potential impacts of climate change on our economy and markets. Projected economic outcomes depend on many uncertain factors, including technological developments, economic growth, mitigation policies, individual behavioral responses, and Earth system processes. Recognizing this uncertainty is important for decision-making and should be factored into economic planning and risk analysis.

Economic uncertainty due to climate change is costly. Individuals and investors dislike uncertainty as it can drive up costs of action by requiring planning for multiple possible futures. Society thus benefits from actions that can reduce this uncertainty (e.g., obtaining better information on damages). When uncertainty cannot be reduced, some investments may be valuable specifically because they serve as a hedge against climate risks,[159] and it may be prudent to preserve and develop options and invoke decision strategies that seek robustness against a range of future outcomes. For example, in the face of uncertainty around future climate conditions, the California Public Utilities Commission now asks energy utilities to use downscaled climate projections for a very high scenario (RCP8.5) for climate adaptation planning, investment, and operational purposes (see KM 18.3).[165]

## Key Message 19.3

## Economic Opportunities for Households, Businesses, and Institutions Will Change

Climate change is projected to impose a variety of new or higher costs on most households and to impact their employment, income, and quality of life (*very likely*, *high confidence*). Climate change will alter the economic landscape that businesses face, generating new risks but also creating new opportunities (*likely*, *medium confidence*). Institutions and governments are expected to see existing programs used more intensively or in new ways as populations cope with climate change, generating new system-wide risks (*medium confidence*). Design, evaluation, and deployment of adaptation technologies and policies will strengthen our national preparedness for climate change (*high confidence*).

### American Households

Climate change will have different economic implications for American households depending on their occupation and where they live.[84,157] On average, climate change is projected to reduce future income gains compared to what households would achieve in the absence of climate change.[166]

Climate change is expected to impact employment by changing demand for workers, reducing worker safety,[4] altering the location of available jobs,[49] and changing workplace conditions in heat-exposed jobs.[45,167] Households may also lose wealth through declines in the value of real estate (Figure 19.3).

Climate change will affect household spending,[168] for example, by changing energy use (Ch. 5),[169] increasing medical costs (Ch. 15),[143] elevating food prices (Ch. 11),[111] raising insurance premiums, and requiring more frequent repairs and replacement of assets damaged by extreme events.[16]

Children's economic prospects will be affected by climate change. For example, higher temperatures in utero negatively impact adult economic outcomes,[60] while higher temperatures during childhood reduce learning[56,170] and cognitive performance.[171,172]

Climate change is expected to alter the quality of life for American households[125] by reducing life expectancy,[7] increasing crime and domestic violence,[15,173] damaging sleep quality,[174] harming mental health,[6,175] reducing happiness,[176] and altering recreation in both positive and negative ways (Table 19.1).[75,177,178,179]

Adapting to climate change generates new household costs and can alter living and work arrangements. For example, homes may be relocated or retrofitted to withstand weather extremes,[180,181] and consumption patterns may change to offset harms from the climate.[62] Importantly, lower-income households may face greater risks from climate change and have fewer resources to support the costs of adaptation (KMs 22.3, 22.4).[98]

### American Businesses

Climate change is projected to reduce labor productivity and economic output across many sectors—including agriculture, finance, real estate, insurance, and services—and across many regions and states.[15,80,157] Extreme weather events can reduce output for extended periods, altering GDP growth rates.[158] In projections, these effects can compound over time, generating large cumulative losses.[9,31,157,182]

Businesses will face increasing exposure to climate-related risks at local, national, and international levels. For example, more intense heatwaves will reduce local productivity, greater wildfire smoke will lower

demand for outdoor services, and more frequent extreme events around the world will disrupt international trade, supply chains, and foreign demand for American products (KM 17.3).

Climate change will also affect business investment planning. For example, the location of firm capital investments may change in response to more frequent weather disasters,[183] and regional adaptation efforts may be funded via corporate taxes or impact the rate of return on other investments.[184] Investment strategies for climate-resilient technologies and the total cost of insurance for capital investments are both expected to be impacted by climate change. In addition, uncertainty in impacts and the effectiveness of adaptation may delay investments (see Box 19.1).

The management of climate-related business risks can draw on established practices for general risk management. For example, regulators and investors are increasingly requiring businesses to disclose climate risks and management strategies. To support this, risk assessment tools for quantifying physical risks are currently being developed in public and private sectors.[185,186]

## Governments and Institutions

Local, regional, national, and international governments and institutions (e.g., universities, professional associations, nongovernmental organizations) play a major role in facilitating individual and coordinated adaptation responses and enabling cost-effective decisions. Federal agencies are required to develop adaptation plans[187] and assess and mitigate climate-related financial risks,[188] while some states, local governments, and Tribal governments are developing plans varying in scope and complexity (KMs 31.1, 31.3, 31.4, 32.5).

Governments at all levels would benefit from preparing for the fiscal impacts of climate change, considering impacts on revenues, expenditure requirements (e.g., healthcare, income support), and borrowing costs.[53,68,128] Reducing the overall societal cost of extreme events may be possible through investments in public infrastructure, healthcare, and community resilience programs[189,190,191] and through public support for private adaptation, including fiscal support,[76] updated building codes (Ch. 12),[192,193,194] and better climate-risk information and disclosures.[195] Such public programs also have the potential to reduce the inequitable impacts of climate change.[98,196] Financial preparedness by households and public entities, such as through insurance take-up,[52,197] improved credit,[52,85] and specialized financial instruments,[198] can shift risk or reduce losses. However, public insurance support or provision can decrease incentives for private adaptation.[76,199]

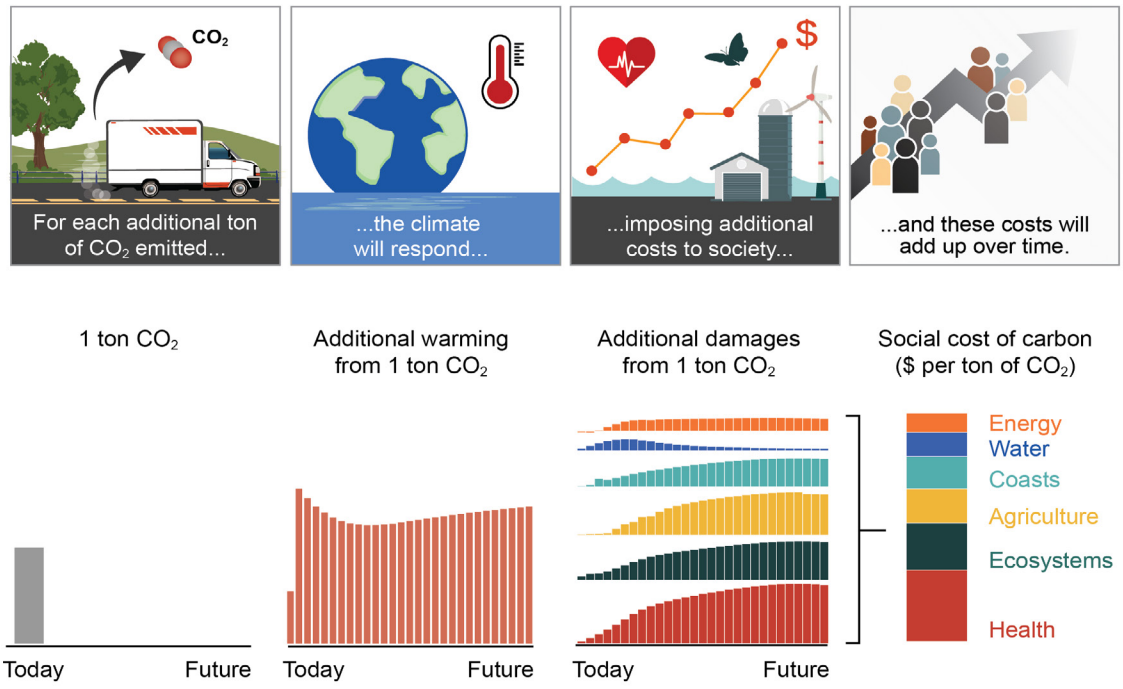
It is sometimes important for governments or institutions to quantify the overall economic impact of climate changes caused by certain current activities, for example, in analyses of whether the benefits of a new climate policy exceed its costs. A succinct summary description of the benefits of emissions reductions widely used in economic analyses is the "social cost of greenhouse gases," defined as the cumulative global economic harm to society caused by additional greenhouse gas emissions (Figure 19.5).[200] Institutions and governments considering the economic consequences of emissions may find estimates of this measure helpful, although they should familiarize themselves with the analytical and ethical judgments used in its construction. In 2010, twelve agencies from the Federal Government developed a process for estimating the social cost of greenhouse gases and periodically updated it based on scientific advances.[201] The current interim estimate used by the Federal Government, adjusted to 2022 dollars, is $57, $1,700, and $20,000 per ton of carbon dioxide, methane, and nitrous oxide, respectively, for 2020 emissions using a 3% discount rate.[201] There is ongoing research to update these values in accordance with recommendations from the National Academies of Sciences, Engineering, and Medicine.[200]

There is growing concern that climate change could pose a systemic risk to financial stability.[202,203,204,205,206,207] Negative economic impacts on even a limited number of entities could, in principle, lead to cascading effects, causing wider failure in the financial system. For example, declines in property values due to climate

change could adversely affect mortgage markets and financial institutions' balance sheets, potentially leading to financial distress, especially if climate risks are imperfectly priced or if they are concentrated in government-sponsored enterprises.[202,206,207,208,209,210] While more research is needed to understand these systemic effects, some underlying risks can be managed. For example, the risk of future asset price corrections, driven by misalignment between current prices and the expected effects of climate change,[57,101,102,103,109,211] can be reduced through communication and disclosure of climate risks to market actors.[109,195]

Climate change has the potential to undermine conditions that support overall societal stability, which may threaten economic stability, and vice versa. Global warming has the potential to impede the ability of institutions and governmental organizations to function smoothly[175,212] and to increase political turnover,[213] and it is directly implicated in increasing rates of violence and unrest.[214,215] Some extreme events have triggered widespread mortgage delinquency,[216] insurer default,[217] breakdown in support for leaders,[218] and the migration of large populations domestically[219,220] and internationally[221,222]—which in turn impacts downstream markets.[146,223] Coping with these destabilizing effects may require investment in systems that buffer and stabilize economic and social conditions, such as social safety nets, insurance, defense spending, and confidence-building mechanisms.[54,133,224]

## The Social Cost of Greenhouse Gases




**The social cost of greenhouse gases is a monetary estimate of the total economic impact of an additional greenhouse gas emission today.**

**Figure 19.5.** The social cost of greenhouse gases provides an estimate of the economic benefits to society of mitigating emissions, which can then be compared against the costs of doing so. This conceptual illustration shows how the social cost of reducing emissions of a particular greenhouse gas is computed. From left to right, the effect of one ton of carbon dioxide ($CO_2$) emitted into the atmosphere is illustrated in terms of additional warming or other physical impacts like sea level rise; these changes are translated into costs and benefits expected in representative market sectors such as agriculture, energy services, and water and coastal resources, as well as nonmarket impacts to human health and ecosystems; lastly, impacts that occur around the world and into the future are added up into a single measure using weights that reflect preferences around time, risk, and equity. The values shown in the figure are illustrative and may differ from estimates used for regulatory purposes. Figure credit: See figure metadata for contributors.

# Traceable Accounts

## *Process Description*

The chapter lead author was identified in July 2021, and the author team was recruited in July–August of 2021. Authors were selected based on their expertise on broad topics critical to the economic impacts of climate change on the US economy. Technical contributors were recruited by January of 2022 and were identified based on their expertise on specific types of impact. Efforts were made to ensure that both the author team and technical contributors represented a diverse range of backgrounds from across the country, including representation from academia, the private sector, nongovernmental organizations, and economic units of the Federal Government. The Economics chapter hosted an online engagement workshop on January 31, 2022. The authors also considered other outreach with stakeholders and inputs provided in the public call for technical material and incorporated the available scientific literature to write the chapter.

Discussion within the team during multiple virtual meetings and email exchanges, along with consideration of a systematic review of available scientific literature developed by the technical contributors, led to the development of three Key Messages. Because previous National Climate Assessments did not have a chapter on economics, the team focused on scientific material that was not previously discussed in other chapters of prior Assessments. Based on scoping by the National Climate Assessment Federal Steering Committee, the Economics chapter focused on the economic impact of climate change on the US economy and did not consider economic aspects of potential mitigation policies, which was out of scope. Particular attention was paid to the emerging scientific understanding of inequity of impacts across the country, which informed all Key Messages. Figures were developed by the author team, with support from technical contributors, to highlight key concepts that support the Key Messages. Entries to the tables of example impacts (Table 19.1) were selected, based on an evaluation of their topical importance and breadth of coverage, from a much larger database of more than 300 entries collected by the author team and technical contributors in their review of scientific evidence.

## Key Message 19.1

## Climate Change Affects the Economy Directly

### Description of Evidence Base

There is mounting evidence of climate change impacts on economic costs. This literature requires multi-disciplinary expertise bridging the physical sciences and economics. Broadly, the approaches to estimating climate impacts include biophysical process models, structural economic models, statistical or empirical methods, and hybrid approaches, with each methodology having strengths and weaknesses. A common finding in the above literature[26,38,39,225] is that moderate temperature and/or rainfall are usually beneficial, while cold and heat spells negatively affect a sector, as do droughts and floods. This implies that impacts will vary by 1) the baseline climate, 2) the predicted change, and 3) the vulnerability to such changes. First, colder places might actually benefit from warming as colder temperatures are replaced with moderate ones. Most of the above papers find an asymmetric relationship with regard to temperature, where being too hot is worse than being too cold. Hence, the effect of an increase in extreme heat is the dominant driver for most places in the US leading to a net loss. Second, predicted climate change is not uniform around the world, and higher latitudes (farther removed from the equator) are predicted to see higher warming. Third, vulnerabilities vary significantly across groups; for example, the sensitivity to extreme heat is larger in cold places,[226] and poorer places tend to have higher mortality effects of hotter temperatures.[7]

The literature addresses adaptation either by assessing it directly or assuming results are inclusive of adaptive responses.[7] Examples of directly assessing adaptation include study of the development and penetration of air-conditioning to reduce future temperature-related mortality,[38] the use of drought-tolerant crop varieties to limit the impact of some historical climate events,[161] and the building of seawalls and nourishment of beaches to protect infrastructure and ecosystems from sea level rise.[40] Research often assumes optimal adaptation, but some studies have considered partial adaptation to be more reflective of observed reality.[227]

## Major Uncertainties and Research Gaps

A major source of uncertainty in estimates of climate change's economic impacts is representing complex interactions among physical, natural, and social systems. There are a number of critiques of the existing literature but also many important advances. Major uncertainties arise around unmeasured impacts, damages due to non-gradual weather or climate changes, interactions between regions and sectors, projections of population and income growth and technological change, risk aversion, distributional effects, and accounting for adaptation processes and costs. Improving the robustness of economic impact estimates is an active area of research. Scientific advancements in the last decade (National Academies of Sciences, Engineering, Medicine 2017[200] and others) have improved estimates of economic impacts, as well as our understanding of key uncertainties.

One point of uncertainty regards the shape or functional form of the climate damage function. While many empirical studies have found that the increase in global, regional, and sectoral damages as the climate warms can be approximated by a quadratic damage function,[15,47,228] disagreement remains, particularly for higher temperatures. Several studies (Nordhaus 2019; Dietz et al. 2021; Kemp et al. 2022;[229,230,231] see also Dietz et al. 2022[232] reply to comments by Keen et al. 2022[233]) argue that the damage function should become substantially steeper at higher levels of warming.

Damage projections in many sectors do not fully account for expected reductions in future vulnerabilities, for example, as has been observed in the past for temperature-related mortality.[7,38] More study of how the relationship between sensitivity of impact sectors (such as agricultural yields, mortality, or energy consumption) to weather fluctuations and income has changed over time may improve this area of research, as it remains unknown whether confounding factors influence cross-sectional comparisons sometimes used to estimate patterns of adaptation. Damage projections also rely on projections of future population, income, and technology, which are themselves uncertain.

## Description of Confidence and Likelihood

There is *high confidence* that climate change will directly affect the economy and that impacts will be unevenly distributed, because numerous information sources document these results across many sectors, and studies of the same outcomes generally agree on the sign and magnitude of these impacts. Many findings are replicated by distinct author teams. Furthermore, insights from biology and physiology, derived from experimental and/or observational data, often support econometric findings. However, the changes in the primary drivers of some of these impacts have complex patterns (e.g., wildfires, floods, drought, hurricanes), while some regions or impact categories may see benefits from warming (e.g., avoided heating expenditures). Therefore, taken together, the finding regarding the substantial cost of these impacts is deemed only *likely*. This same complexity supports the finding of unequal distribution of impacts, so that finding is deemed *very likely*. This unequal distribution is a direct consequence of the different baseline climate (known by looking at current climate), different amount of warming (consistent finding in climate models), and different underlying vulnerabilities due to social determinants such as sensitivity and adaptive capacity. The finding that currently warm places are more negatively impacted by additional warming than colder places is widely supported and garners *high confidence*. Similarly, the fact that vulnerabilities vary by income and education has also been repeatedly observed. Neither point is controversial in the literature.

Given the breadth of approaches to analyzing adaptation, the literature is more varied in conclusions drawn regarding the level of risk that adaptation is expected to ameliorate, the cost of the adaptation actions, and the likelihood that these adaptation actions will actually be implemented. Future innovations may reduce the costs of existing adaptation technologies, or they may result in entirely new technologies. However, some adaptation challenges have proven difficult to overcome,[162] and, ultimately, success is uncertain and there do not exist established approaches for forecasting these innovations. Furthermore, public efforts to adapt to the climate sometimes have perverse outcomes, and it is unclear that similar efforts will be dramatically more successful in the future. For example, in the United States, public provision of both crop insurance subsidies and disaster aid have been estimated to increase vulnerability to extreme weather.[76,199] For all of these reasons, there is only *medium confidence* in findings regarding adaptation.

## Key Message 19.2

## Markets and Budgets Respond to Climate Change

### Description of Evidence Base

Multiple lines of evidence, including theoretical and empirical analyses, demonstrate effects of anticipated climate risks on financial markets. For example, anticipated increases in flood risks due to sea level rise reduce the prices of vulnerable coastal properties[57,101,103] and the prices of long-term bonds issued by vulnerable municipalities.[52,119] These effects have increased over time, coinciding with increasing investor attention to climate change.[57,119,234] Emerging evidence demonstrates potential sources of market inefficiencies due to government policies. For example, existing securitization programs by government-sponsored enterprises, such as Fannie Mae and Freddie Mac, unintentionally encourage banks to issue mortgage loans to properties that are exposed to hurricane risks.[209]

For public budgets, adverse fiscal impacts of more frequent and intense natural disasters are well established. Hurricanes increase public expenditure requirements for healthcare and other programs,[54,132] decrease local tax revenues,[100] and increase municipal borrowing costs.[100] Wildfires have similarly been shown to increase public expenditures on fire suppression and other programs.[53,68,135,192,235,236,237] Evidence on natural disaster impacts on tax revenues is mixed across event types and levels of government (e.g., Liao and Kousky 2022[53]) find positive local revenue impacts of wildfires in California, due to a unique state law that freezes property assessments for taxes until a sale, and Miao et al. (2018)[163] fail to detect significant tax revenue impacts of disasters at the state level). Certain climate impacts may also have partial fiscal benefits, although the evidence is less strong (e.g., EPA 2017;[164] Barrage 2023[68]). However, the same evidence base also suggests negative *net* impacts. For example, Liao and Kousky (2022)[53] estimate large increases in the probability of municipal deficits as a result of wildfire events. Conceptually, disasters such as hurricanes and flooding can also have adverse impacts on tax bases, such as through negative effects on economic growth[51,65,101] and property values.[109,123,131] Finally, the literature documents other fiscal climate costs, such as from infrastructure,[164] the Endangered Species Act,[136] and increasing exposure to flood risk in the balance sheets of financial institutions[208] and government-sponsored enterprises.[209]

For insurance, private markets are important for financial resilience and climate adaptation, but these markets may be stressed by climate change. For example, it is well understood that as climate risks grow, it is increasingly difficult for insurers to offer policies at rates that both reflect risks accurately and that consumers are able and willing to pay, leading to a growing disaster insurance gap (e.g., Issler et al. 2020;[238] Netusil et al. 2021;[239] Kousky 2022[113]). Current risk and, thus, insurance pricing systems may become outdated with changing climatic conditions (e.g., GAO 2021[240]). Evidence suggests that households and businesses

with insurance tend to recover better and faster from disasters (reviewed in Kousky 2019,[114] also Billings et al. 2022[85]).

There is growing evidence that global supply chains can transfer, amplify, or reduce the direct impacts of climate change. Multiple studies have documented that climate events in other countries impact trade with the United States, which in turn affects US domestic market conditions.[110,153,154] A smaller number of studies have identified ways that climate change also causes physical events that impact entire regions, generating costs that can be amplified by production networks.[155,241] It is theoretically well understood that flexible supply chain networks can also enable adaptation to climate change by enabling geographic diversification,[156] although there is not a large body of empirical evidence to demonstrate how this occurs in practice.

## Major Uncertainties and Research Gaps

There is considerable uncertainty regarding the estimated effects of climate risk exposure on asset values. For example, estimates of the effect of sea level rise risk on coastal real estate prices vary from as large as –20%[57] to zero.[211] There is also substantial uncertainty about the extent of exposure of financial institutions to climate-related risks.[205] More research would be needed to understand how climate risks affect prices and quantities in debt markets, especially the mortgage market and mortgage-backed security market, and to understand the potential sources of market inefficiencies in pricing and allocating climate risks.

For public budgets, while evidence suggests that many public program costs may be affected by climate change, many of these impacts remain unquantified (e.g., law enforcement and military expenditure changes due to potential increases in crime and international conflict, respectively). Research is also limited on interactions between different climate impacts, such as on migration and fiscal outcomes. For both public budgets and insurance markets, policy uncertainty and uncertainty over adaptation compound the difficulty in projecting climate impacts.

## Description of Confidence and Likelihood

There is evidence of market responses to climate change, although the literature on this topic varies in terms of estimates of the magnitude and timing of the response, which leads to a determination of *medium confidence* for this finding. However, climate risk factors are *very likely* to be an important driver of asset values in the future. There is already a significant body of research documenting the capitalization of weather-related risks into the prices of durable assets (real estate, stocks, long-term bonds, etc.), including a growing number of papers finding a reflection of the assets' exposure to future climate risks (e.g., sea level rise, flooding, wildfires, or anticipated carbon policies), leading to a determination that this linkage is *very likely*, although the magnitude varies and estimates of how price changes will unfold over time are uncertain. The literature on this is robust enough to warrant *high confidence*. There is *high confidence* that climate change will stress insurance systems and public budgets that were designed before global warming. This is supported by a large academic literature that considers direct effects of climate change on insured assets such as crops and flood-prone homes, direct effects on publicly funded disaster assistance, and indirect effects on healthcare utilization and social safety net programs. There is also research confirming negative impacts on municipal budgets from natural disasters and projected losses to other public sector budgets. In addition, there is mounting observational evidence of climate stress already impacting markets in certain regions of the country such as Louisiana, Florida, Texas, and California. There is *medium confidence* that trade and economic growth are both *likely* to be impacted by climate changes and by the policy responses designed to mitigate climate change. There is broad agreement that climate change will affect trade, but the magnitude and structure of those changes are complex and not fully understood. Similarly, many studies find that climate change affects economic growth, but there is substantial variation in quantitative results depending on which methods and data are used.

## Key Message 19.3

# Economic Opportunities for Households, Businesses, and Institutions Will Change

### Description of Evidence Base

Substantial literature supports the conclusion that climate change will impose new costs on households and businesses.[15,84,157] In particular, research has focused on income,[15,31,157,166,242,243,244] employment,[4,39,49,167] and changes in real estate value.[57,101,103,105,211] Businesses face increased costs in a variety of areas. These costs include reduced productivity due to heatwaves, lower demand for outdoor activity at more distant locations due to wildfire smoke, supply chain disruption due to hydrologic extreme events (e.g., tropical cyclones in Asia, where semiconductor manufacturing is concentrated), property damage and business interruption losses from weather-related extremes,[245,246] and reduced foreign demand for American products.[5,84,156]

Literature also supports the fact that it is possible to reduce the societal cost of extreme climate-related events through investments in hazard mitigation,[3,76,247] including updated building codes[192,193,194,248,249] and public provision of better climate-risk information, such as flood risk disclosures.[195,250] Research has also shown that existing and new programs and activities associated with public and private institutions will need to play a role in helping to mitigate and adapt to climate change.[52,53,54,68,100,128,135,163] Household financial preparedness and specialized financial instruments[198] can also play a role in reducing losses from climate extremes. While insurance against natural disasters can financially protect households and businesses, these markets are themselves being stressed by climate change, with much natural disaster coverage now offered through fully or quasi-public programs.[113] It remains the case that those most in need of the financial protection of insurance are least able to afford it. There is strong evidence that public healthcare and social support programs can reduce climate vulnerability in certain settings.[190,191]

### Major Uncertainties and Research Gaps

It is challenging to anticipate all the ways that households, businesses, and institutions will change in the face of a wide range of climate impacts; continued research on observed and projected responses to climate changes will refine and improve quantitative estimates of the implications of these changes. In particular, systemic risks have proven more difficult to conceptualize and model, and while they could be extremely costly, they have received less research attention. We also have limited understanding of nonlinearities in the costs or threshold effects that may materialize in both natural and human systems. Public programs can potentially moderate the inequality of climate impacts in important ways, but more research would be required to identify cost-effective and scalable strategies.[251] There are also uncertainties regarding how to target healthcare and other social support programs to achieve the largest net benefits.

### Description of Confidence and Likelihood

There is a large literature base and high agreement regarding the variety of new or higher costs of climate change, leading to the finding of *very likely* and *high confidence* for this statement. There is less literature available characterizing the alteration of the economic landscape due to climate change, and while new risks predominate, there is a subset of papers that discuss the potential for new opportunities that business can take advantage of: this leads to the *likely* and *medium confidence* finding. Similarly, there is less literature regarding the response of institutions to changing climate conditions, leading to a *medium confidence* finding. There is extensive literature and a high level of agreement that private and public investments in adaptation and mitigation can reduce household and business costs, leading to the assessment of *high confidence*.

# References


1. DOS and EOP, 2021: The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. U.S. Department of State and U.S. Executive Office of the President, Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2021/10/us-long-term-strategy.pdf

2. Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G.P. Peters, A. Rao, S. Robertson, A.M. Sebbit, J. Steinberger, M. Tavoni, and D.P. van Vuuren, 2022: Ch. 3. Mitigation pathways compatible with long-term goals. In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A.A. Khourdajie, R.v. Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 295–408. https://doi.org/10.1017/9781009157926.005

3. Neumann, J.E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich, 2021: Climate effects on US infrastructure: The economics of adaptation for rail, roads, and coastal development. *Climatic Change*, **167** (3), 44. https://doi.org/10.1007/s10584-021-03179-w

4. Park, R.J., N. Pankratz, and A.P. Behrer, 2021: Temperature, Workplace Safety, and Labor Market Inequality. IZA DP No. 14560. IZA Institute of Labor Economics. https://docs.iza.org/dp14560.pdf

5. D'Agostino, A.L. and W. Schlenker, 2016: Recent weather fluctuations and agricultural yields: Implications for climate change. *Agricultural Economics*, **47** (S1), 159–171. https://doi.org/10.1111/agec.12315

6. Burke, M., F. González, P. Baylis, S. Heft-Neal, C. Baysan, S. Basu, and S. Hsiang, 2018: Higher temperatures increase suicide rates in the United States and Mexico. *Nature Climate Change*, **8** (8), 723–729. https://doi.org/10.1038/s41558-018-0222-x

7. Carleton, T., A. Jina, M. Delgado, M. Greenstone, T. Houser, S. Hsiang, A. Hultgren, R.E. Kopp, K.E. McCusker, I. Nath, J. Rising, A. Rode, H.K. Seo, A. Viaene, J. Yuan, and A.T. Zhang, 2022: Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. *The Quarterly Journal of Economics*, **137** (4), 2037–2105. https://doi.org/10.1093/qje/qjac020

8. Dodgen, D., D. Donato, N. Kelly, A. La Greca, J. Morganstein, J. Reser, J. Ruzek, S. Schweitzer, M.M. Shimamoto, K. Thigpen Tart, and R. Ursano, 2016: Ch. 8. Mental health and well-being. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 217–246. https://doi.org/10.7930/j0tx3c9h

9. Heutel, G., N.H. Miller, and D. Molitor, 2021: Adaptation and the mortality effects of temperature across U.S. climate regions. *The Review of Economics and Statistics*, **103** (4), 740–753. https://doi.org/10.1162/rest_a_00936

10. Wen, J. and M. Burke, 2022: Lower test scores from wildfire smoke exposure. *Nature Sustainability*, **5** (11), 947–955. https://doi.org/10.1038/s41893-022-00956-y

11. Fisichelli, N.A., G.W. Schuurman, W.B. Monahan, and P.S. Ziesler, 2015: Protected area tourism in a changing climate: Will visitation at US national parks warm up or overheat? *PLoS ONE*, **10** (6), e0128226. https://doi.org/10.1371/journal.pone.0128226

12. Lipton, D., M. Rubenstein, S.R. Weiskopf, S. Carter, J. Peterson, L. Crozier, M. Fogarty, S. Gaichas, K.J.W. Hyde, T.L. Morelli, J. Morisette, H. Moustahfid, R. Muñoz, R. Poudel, M.D. Staudinger, C. Stock, L. Thompson, R. Waples, and J.F. Weltzin, 2018: Ch. 7. Ecosystems, ecosystem services, and biodiversity. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 268–321. https://doi.org/10.7930/nca4.2018.ch7

13. Pershing, A., K. Mills, A. Dayton, B. Franklin, and B. Kennedy, 2018: Evidence for adaptation from the 2016 marine heatwave in the Northwest Atlantic Ocean. *Oceanography*, **31** (2), 152–161. https://doi.org/10.5670/oceanog.2018.213

14. Dietz, S. and N. Stern, 2015: Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. *The Economic Journal*, **125** (583), 574–620. https://doi.org/10.1111/ecoj.12188

15. Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D.J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser, 2017: Estimating economic damage from climate change in the United States. *Science*, **356** (6345), 1362–1369. https://doi.org/10.1126/science.aal4369

16. NCEI, 2022: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

17. Swain, D.L., O.E.J. Wing, P.D. Bates, J.M. Done, K.A. Johnson, and D.R. Cameron, 2020: Increased flood exposure due to climate change and population growth in the United States. *Earth's Future*, **8** (11), e2020EF001778. https://doi.org/10.1029/2020ef001778

18. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

19. Zhang, Y. and D.T. Shindell, 2021: Costs from labor losses due to extreme heat in the USA attributable to climate change. *Climatic Change*, **164** (3), 35. https://doi.org/10.1007/s10584-021-03014-2

20. Walther, G.-R., 2010: Community and ecosystem responses to recent climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365** (1549), 2019–2024. https://doi.org/10.1098/rstb.2010.0021

21. Ortiz-Bobea, A., H. Wang, C.M. Carrillo, and T.R. Ault, 2019: Unpacking the climatic drivers of US agricultural yields. *Environmental Research Letters*, **14** (6), 064003. https://doi.org/10.1088/1748-9326/ab1e75

22. Asseng, S., F. Ewert, P. Martre, R.P. Rötter, D.B. Lobell, D. Cammarano, B.A. Kimball, M.J. Ottman, G.W. Wall, J.W. White, M.P. Reynolds, P.D. Alderman, P.V.V. Prasad, P.K. Aggarwal, J. Anothai, B. Basso, C. Biernath, A.J. Challinor, G. De Sanctis, J. Doltra, E. Fereres, M. Garcia-Vila, S. Gayler, G. Hoogenboom, L.A. Hunt, R.C. Izaurralde, M. Jabloun, C.D. Jones, K.C. Kersebaum, A.K. Koehler, C. Müller, S. Naresh Kumar, C. Nendel, G. O'Leary, J.E. Olesen, T. Palosuo, E. Priesack, E. Eyshi Rezaei, A.C. Ruane, M.A. Semenov, I. Shcherbak, C. Stöckle, P. Stratonovitch, T. Streck, I. Supit, F. Tao, P.J. Thorburn, K. Waha, E. Wang, D. Wallach, J. Wolf, Z. Zhao, and Y. Zhu, 2015: Rising temperatures reduce global wheat production. *Nature Climate Change*, **5**, 143–147. https://doi.org/10.1038/nclimate2470

23. Moore, F.C., U.L.C. Baldos, and T. Hertel, 2017: Economic impacts of climate change on agriculture: A comparison of process-based and statistical yield models. *Environmental Research Letters*, **12** (6), 065008. https://doi.org/10.1088/1748-9326/aa6eb2

24. Ortiz-Bobea, A., T.R. Ault, C.M. Carrillo, R.G. Chambers, and D.B. Lobell, 2021: Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change*, **11** (4), 306–312. https://doi.org/10.1038/s41558-021-01000-1

25. Proctor, J., A. Rigden, D. Chan, and P. Huybers, 2022: More accurate specification of water supply shows its importance for global crop production. *Nature Food*, **3** (9), 753–763. https://doi.org/10.1038/s43016-022-00592-x

26. Schlenker, W. and M.J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **106** (37), 15594–15598. https://doi.org/10.1073/pnas.0906865106

27. Tack, J., A. Barkley, and L.L. Nalley, 2015: Effect of warming temperatures on US wheat yields. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (22), 6931–6936. https://doi.org/10.1073/pnas.1415181112

28. Welch, J.R., J.R. Vincent, M. Auffhammer, P.F. Moya, A. Dobermann, and D. Dawe, 2010: Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, **107** (33), 14562–14567. https://doi.org/10.1073/pnas.1001222107

29. Neumann, J.E., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2015: Climate change risks to US infrastructure: Impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*, **131** (1), 97–109. https://doi.org/10.1007/s10584-013-1037-4

30. Dasgupta, P., 2021: The Economics of Biodiversity: The Dasgupta Review. HM Treasury, London, UK. https://www.gov.uk/government/publications/final-report-the-economics-of-biodiversity-the-dasgupta-review

31. Burke, M., S.M. Hsiang, and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527** (7577), 235–239. https://doi.org/10.1038/nature15725

32. Willner, S.N., N. Glanemann, and A. Levermann, 2021: Investment incentive reduced by climate damages can be restored by optimal policy. *Nature Communications*, **12** (1), 3245. https://doi.org/10.1038/s41467-021-23547-5

33. Kimball, B.A., 2016: Crop responses to elevated $CO_2$ and interactions with $H_2O$, N, and temperature. *Current Opinion in Plant Biology*, **31**, 36–43. https://doi.org/10.1016/j.pbi.2016.03.006

34. Myers, S.S., A. Zanobetti, I. Kloog, P. Huybers, A.D.B. Leakey, A.J. Bloom, E. Carlisle, L.H. Dietterich, G. Fitzgerald, T. Hasegawa, N.M. Holbrook, R.L. Nelson, M.J. Ottman, V. Raboy, H. Sakai, K.A. Sartor, J. Schwartz, S. Seneweera, M. Tausz, and Y. Usui, 2014: Increasing $CO_2$ threatens human nutrition. *Nature*, **510** (7503), 139–142. https://doi.org/10.1038/nature13179

35. Hsiang, S. and R.E. Kopp, 2018: An economist's guide to climate change science. *Journal of Economic Perspectives*, **32** (4), 3–32. https://doi.org/10.1257/jep.32.4.3

36. Cai, Y. and T.S. Lontzek, 2019: The social cost of carbon with economic and climate risks. *Journal of Political Economy*, **127** (6), 2684–2734. https://doi.org/10.1086/701890

37. Lemoine, D., 2021: The climate risk premium: How uncertainty affects the social cost of carbon. *Journal of the Association of Environmental and Resource Economists*, **8** (1), 27–57. https://doi.org/10.1086/710667

38. Barreca, A., K. Clay, O. Deschenes, M. Greenstone, and J.S. Shapiro, 2016: Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century. *Journal of Political Economy*, **124** (1), 105–159. https://doi.org/10.1086/684582

39. Graff Zivin, J. and M. Neidell, 2014: Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics*, **32** (1), 1–26. https://doi.org/10.1086/671766

40. Diaz, D.B., 2016: Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). *Climatic Change*, **137** (1), 143–156. https://doi.org/10.1007/s10584-016-1675-4

41. Hsiang, S.M. and D. Narita, 2012: Adaptation to cyclone risk: Evidence from the global cross-section. *Climate Change Economics*, **03** (02), 1250011. https://doi.org/10.1142/s201000781250011x

42. Fant, C., J.M. Jacobs, P. Chinowsky, W. Sweet, N. Weiss, J.E. Sias, J. Martinich, and J.E. Neumann, 2021: Mere nuisance or growing threat? The physical and economic impact of high tide flooding on US road networks. *Journal of Infrastructure Systems*, **27** (4), 04021044. https://doi.org/10.1061/(asce)is.1943-555x.0000652

43. Hultgren, A., T. Carleton, M. Delgado, D.R. Gergel, M. Greenstone, T. Houser, S. Hsiang, A. Jina, R.E. Kopp, S.B. Malevich, K. McCusker, T. Mayer, I. Nath, J. Rising, A. Rode, and J. Yuan, 2022: Estimating Global Impacts to Agriculture from Climate Change Accounting for Adaptation. Social Science Research Network, 112 pp. https://doi.org/10.2139/ssrn.4222020

44. Martinich, J. and A. Crimmins, 2019: Climate damages and adaptation potential across diverse sectors of the United States. *Nature Climate Change*, **9** (5), 397–404. https://doi.org/10.1038/s41558-019-0444-6

45. Rode, A., R.E. Baker, T. Carleton, A. D'Agostino, M. Delgado, T. Foreman, D.R. Gergel, M. Greenstone, T. Houser, S. Hsiang, A. Hultgren, A. Jina, R.E. Kopp, S.B. Malevich, K.E. McCusker, I. Nath, M. Pecenco, J. Rising, and J. Yuan, 2022: Labor Disutility in a Warmer World: The Impact of Climate Change on the Global Workforce. Social Science Research Network, 96 pp. https://doi.org/10.2139/ssrn.4221478

46. Rode, A., T. Carleton, M. Delgado, M. Greenstone, T. Houser, S. Hsiang, A. Hultgren, A. Jina, R.E. Kopp, K.E. McCusker, I. Nath, J. Rising, and J. Yuan, 2021: Estimating a social cost of carbon for global energy consumption. *Nature*, **598** (7880), 308–314. https://doi.org/10.1038/s41586-021-03883-8

47. Sarofim, M.C., J. Martinich, J.E. Neumann, J. Willwerth, Z. Kerrich, M. Kolian, C. Fant, and C. Hartin, 2021: A temperature binning approach for multi-sector climate impact analysis. *Climatic Change*, **165** (1), 22. https://doi.org/10.1007/s10584-021-03048-6

48. Diffenbaugh, N.S., F.V. Davenport, and M. Burke, 2021: Historical warming has increased U.S. crop insurance losses. *Environmental Research Letters*, **16** (8), 084025. https://doi.org/10.1088/1748-9326/ac1223

49. Feng, S., M. Oppenheimer, and W. Schlenker, 2012: Climate Change, Crop Yields, and Internal Migration in the United States. Working Paper 17734. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w17734

50. Holtermans, R., M.E. Kahn, and N. Kok, 2022: Climate Risk and Commercial Mortgage Delinquency. Research Paper No. 22/04. MIT Center for Real Estate, 36 pp. https://doi.org/10.2139/ssrn.4066875

51. Strobl, E., 2011: The economic growth impact of hurricanes: Evidence from U.S. coastal counties. *The Review of Economics and Statistics*, **93** (2), 575–589. https://doi.org/10.1162/rest_a_00082

52. Painter, M., 2020: An inconvenient cost: The effects of climate change on municipal bonds. *Journal of Financial Economics*, **135** (2), 468–482. https://doi.org/10.1016/j.jfineco.2019.06.006

53. Liao, Y. and C. Kousky, 2022: The fiscal impacts of wildfires on California municipalities. *Journal of the Association of Environmental and Resource Economists*, **9** (3), 455–493. https://doi.org/10.1086/717492

54. Deryugina, T., 2017: The fiscal cost of hurricanes: Disaster aid versus social insurance. *American Economic Journal: Economic Policy*, **9** (3), 168–198. https://doi.org/10.1257/pol.20140296

55. Beltrán, A., D. Maddison, and R.J.R. Elliott, 2018: Is flood risk capitalised into property values? *Ecological Economics*, **146**, 668–685. https://doi.org/10.1016/j.ecolecon.2017.12.015

56. Park, R.J., J. Goodman, M. Hurwitz, and J. Smith, 2020: Heat and learning. *American Economic Journal: Economic Policy*, **12** (2), 306–339. https://doi.org/10.1257/pol.20180612

57. Bernstein, A., M.T. Gustafson, and R. Lewis, 2019: Disaster on the horizon: The price effect of sea level rise. *Journal of Financial Economics*, **134** (2), 253–272. https://doi.org/10.1016/j.jfineco.2019.03.013

58. Davenport, F.V., M. Burke, and N.S. Diffenbaugh, 2021: Contribution of historical precipitation change to US flood damages. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (4), e2017524118. https://doi.org/10.1073/pnas.2017524118

59. Borgschulte, M., D. Molitor, and E. Zou, 2022: Air Pollution and the Labor Market: Evidence from Wildfire Smoke. Working Paper 29952. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w29952

60. Isen, A., M. Rossin-Slater, and R. Walker, 2017: Relationship between season of birth, temperature exposure, and later life wellbeing. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (51), 13447–13452. https://doi.org/10.1073/pnas.1702436114

61. White, C., 2017: The dynamic relationship between temperature and morbidity. *Journal of the Association of Environmental and Resource Economists*, **4** (4), 1155–1198. https://doi.org/10.1086/692098

62. Deschênes, O. and M. Greenstone, 2011: Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the US. *American Economic Journal: Applied Economics*, **3** (4), 152–185. https://doi.org/10.1257/app.3.4.152

63. USACE, 2006: Alaska Village Erosion Technical Assistance Program: An Examination of Erosion Issues in the Communities of Bethel, Dillingham, Kaktovik, Kivalina, Newtok, Shishmaref, and Unalakleet. U.S. Army Corps of Engineers, Alaska District. http://66.160.145.48/coms/cli/AVETA_Report.pdf

64. Lee, J., L. Marla, and P. Vaishnav, 2021: The impact of climate change on the recoverability of airline networks. *Transportation Research Part D: Transport and Environment*, **95**, 102801. https://doi.org/10.1016/j.trd.2021.102801

65. Hsiang, S.M. and A.S. Jina, 2014: The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence From 6,700 Cyclones. Working Paper 20352. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w20352

66. OMB, 2022: Climate Risk Exposure: An Assessment of the Federal Government's Financial Risks to Climate Change. U.S. Office of Management and Budget. https://www.whitehouse.gov/wp-content/uploads/2022/04/omb_climate_risk_exposure_2022.pdf

67. Shi, L. and A.M. Varuzzo, 2020: Surging seas, rising fiscal stress: Exploring municipal fiscal vulnerability to climate change. *Cities*, **100**, 102658. https://doi.org/10.1016/j.cities.2020.102658

68. Barrage, L., 2023: Fiscal Costs of Climate Change in the United States. Economic Working Paper Series 23/380. ETH Zurich, Center of Economic Research. https://doi.org/10.3929/ethz-b-000605514

69. Larsen, P.H., B. Boehlert, J. Eto, K. Hamachi-LaCommare, J. Martinich, and L. Rennels, 2018: Projecting future costs to U.S. electric utility customers from power interruptions. *Energy*, **147**, 1256–1277. https://doi.org/10.1016/j.energy.2017.12.081

70. FSF, 2021: The Cost of Climate: America's Growing Flood Risk. First Street Foundation, 121 pp. https://assets.firststreet.org/uploads/2021/02/The_Cost_of_Climate_FSF20210219-1.pdf

71. Chinowsky, P., J. Helman, S. Gulati, J. Neumann, and J. Martinich, 2019: Impacts of climate change on operation of the US rail network. *Transport Policy*, **75**, 183–191. https://doi.org/10.1016/j.tranpol.2017.05.007

72. BIA, 2020: The Unmet Infrastructure Needs of Tribal Communities and Alaska Native Villages in Process of Relocating to Higher Ground as a Result of Climate Change. Department of Interior, Bureau of Indian Affairs, Albuquerque, NM. https://www.bia.gov/news/unmet-infrastructure-needs-tribal-communities-and-alaska-native-villages-process-relocation

73. Feng, S., A.B. Krueger, and M. Oppenheimer, 2010: Linkages among climate change, crop yields and Mexico–US cross-border migration. *Proceedings of the National Academy of Sciences of the United States of America*, **107** (32), 14257–14262. https://doi.org/10.1073/pnas.1002632107

74. Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara, 2021: The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2011048118. https://doi.org/10.1073/pnas.2011048118

75. Chan, N.W. and C.J. Wichman, 2022: Valuing nonmarket impacts of climate change on recreation: From reduced form to welfare. *Environmental and Resource Economics*, **81** (1), 179–213. https://doi.org/10.1007/s10640-021-00624-3

76. Fried, S., 2022: Seawalls and stilts: A quantitative macro study of climate adaptation. *The Review of Economic Studies*, **89** (6), 3303–3344. https://doi.org/10.1093/restud/rdab099

77. Bierbaum, R., J.B. Smith, A. Lee, M. Blair, L. Carter, F.S. Chapin, P. Fleming, S. Ruffo, M. Stults, S. McNeeley, E. Wasley, and L. Verduzco, 2013: A comprehensive review of climate adaptation in the United States: More than before, but less than needed. *Mitigation and Adaptation Strategies for Global Change*, **18** (3), 361–406. https://doi.org/10.1007/s11027-012-9423-1

78. Burke, M. and K. Emerick, 2016: Adaptation to climate change: Evidence from US agriculture. *American Economic Journal: Applied Economics*, **8** (3), 106–140. https://doi.org/10.1257/pol.20130025

79. Mendelsohn, R., W.D. Nordhaus, and D. Shaw, 1994: The impact of global warming on agriculture: A Ricardian analysis. *The American Economic Review*, **84** (4), 753–771. http://www.jstor.org/stable/pdfplus/2118029.pdf

80. Deryugina, T. and S. Hsiang, 2017: The Marginal Product of Climate. Working Paper 24072. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w24072

81. Schlenker, W., M.J. Roberts, and D.D. Lobell, 2013: US maize adaptability. *Nature Climate Change*, **3**, 690–691. https://doi.org/10.1038/nclimate1959

82. Orlove, B., 2005: Human adaptation to climate change: A review of three historical cases and some general perspectives. *Environmental Science & Policy*, **8** (6), 589–600. https://doi.org/10.1016/j.envsci.2005.06.009

83. Wagner, G. and W. Schlenker, 2022: Declining crop yields limit the potential of bioenergy. *Nature*, **609** (7926), 250–251. https://doi.org/10.1038/d41586-022-02344-0

84. Behrer, A.P., R.J. Park, G. Wagner, C.M. Golja, and D.W. Keith, 2021: Heat has larger impacts on labor in poorer areas. *Environmental Research Communications*, **3** (9), 095001. https://doi.org/10.1088/2515-7620/abffa3

85. Billings, S.B., E.A. Gallagher, and L. Ricketts, 2022: Let the rich be flooded: The distribution of financial aid and distress after Hurricane Harvey. *Journal of Financial Economics*, **146** (2), 797–819. https://doi.org/10.1016/j.jfineco.2021.11.006

86. Emrich, C.T., E. Tate, S.E. Larson, and Y. Zhou, 2020: Measuring social equity in flood recovery funding. *Environmental Hazards*, **19** (3), 228–250. https://doi.org/10.1080/17477891.2019.1675578

87. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

88. Heilmann, K., M.E. Kahn, and C.K. Tang, 2021: The urban crime and heat gradient in high and low poverty areas. *Journal of Public Economics*, **197**, 104408. https://doi.org/10.1016/j.jpubeco.2021.104408

89. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. https://doi.org/10.3390/cli8010012

90. Howell, J. and J.R. Elliot, 2019: Damages done: The longitudinal impacts of natural hazards on wealth inequality in the United States. *Social Problems*, **66** (3), 448–467. https://doi.org/10.1093/socpro/spy016

91. Hsu, A., G. Sheriff, T. Chakraborty, and D. Manya, 2021: Disproportionate exposure to urban heat island intensity across major US cities. *Nature Communications*, **12** (1), 2721. https://doi.org/10.1038/s41467-021-22799-5

92. Mehta, L., S. Srivastava, S. Movik, H.N. Adam, R. D'Souza, D. Parthasarathy, L.O. Naess, and N. Ohte, 2021: Transformation as praxis: Responding to climate change uncertainties in marginal environments in South Asia. *Current Opinion in Environmental Sustainability*, **49**, 110–117. https://doi.org/10.1016/j.cosust.2021.04.002

93. Deryugina, T., G. Heutel, N.H. Miller, D. Molitor, and J. Reif, 2019: The mortality and medical costs of air pollution: Evidence from changes in wind direction. *American Economic Review*, **109** (12), 4178–4219. https://doi.org/10.1257/aer.20180279

94. Albert, S., R. Bronen, N. Tooler, J. Leon, D. Yee, J. Ash, D. Boseto, and A. Grinham, 2018: Heading for the hills: Climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5 °C future. *Regional Environmental Change*, **18** (8), 2261–2272. https://doi.org/10.1007/s10113-017-1256-8

95. Smith, N. and A. Sattineni, 2016: Effect of erosion in Alaskan coastal villages. *52nd ASC Annual International Conference Proceedings*, Provo, UT. Associated Schools of Construction, 7 pp. http://ascpro0.ascweb.org/archives/cd/2016/paper/CPRT151002016.pdf

96. Bakkensen, L.A. and L. Ma, 2020: Sorting over flood risk and implications for policy reform. *Journal of Environmental Economics and Management*, **104**, 102362. https://doi.org/10.1016/j.jeem.2020.102362

97. Varela Varela, A., 2023: Surge of Inequality: How Different Neighborhoods React to Flooding. Federal Reserve Bank of New York, 97 pp. https://doi.org/10.2139/ssrn.4396481

98. Hsiang, S., P. Oliva, and R. Walker, 2019: The distribution of environmental damages. *Review of Environmental Economics and Policy*, **13** (1), 83–103. https://doi.org/10.1093/reep/rey024

99. Roth Tran, B. and T.L. Sheldon, 2017: Same Storm, Different Disasters: Consumer Credit Access, Income Inequality, and Natural Disaster Recovery. Social Science Research Network, 39 pp. https://doi.org/10.2139/ssrn.3380649

100. Jerch, R., M.E. Kahn, and G.C. Lin, 2023: Local public finance dynamics and hurricane shocks. *Journal of Urban Economics*, **134**, 103516. https://doi.org/10.1016/j.jue.2022.103516

101. Bakkensen, L.A. and L. Barrage, 2022: Going underwater? Flood risk belief heterogeneity and coastal home price dynamics. *The Review of Financial Studies*, **35** (8), 3666–3709. https://doi.org/10.1093/rfs/hhab122

102. Hong, H., F.W. Li, and J. Xu, 2019: Climate risks and market efficiency. *Journal of Econometrics*, **208** (1), 265–281. https://doi.org/10.1016/j.jeconom.2018.09.015

103. Baldauf, M., L. Garlappi, and C. Yannelis, 2020: Does climate change affect real estate prices? Only if you believe in it. *The Review of Financial Studies*, **33** (3), 1256–1295. https://doi.org/10.1093/rfs/hhz073

104. Barrage, L. and J. Furst, 2019: Housing investment, sea level rise, and climate change beliefs. *Economics Letters*, **177**, 105–108. https://doi.org/10.1016/j.econlet.2019.01.023

105. Hino, M. and M. Burke, 2021: The effect of information about climate risk on property values. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (17), e2003374118. https://doi.org/10.1073/pnas.2003374118

106. Keenan, J.M. and J.T. Bradt, 2020: Underwaterwriting: From theory to empiricism in regional mortgage markets in the U.S. *Climatic Change*, **162** (4), 2043–2067. https://doi.org/10.1007/s10584-020-02734-1

107. Board of Governors of the Federal Reserve System, 2020: Financial Stability Report. Board of Governors of the Federal Reserve System, Washington, DC. https://www.federalreserve.gov/publications/files/financial-stability-report-20201109.pdf

108. Bolton, P. and M. Kacperczyk, 2021: Do investors care about carbon risk? *Journal of Financial Economics*, **142** (2), 517–549. https://doi.org/10.1016/j.jfineco.2021.05.008

109. Gibson, M. and J.T. Mullins, 2020: Climate risk and beliefs in New York floodplains. *Journal of the Association of Environmental and Resource Economists*, **7** (6), 1069–1111. https://doi.org/10.1086/710240

110. Roberts, M.J. and W. Schlenker, 2013: Identifying supply and demand elasticities of agricultural commodities: Implications for the US ethanol mandate. *American Economic Review*, **103** (6), 2265–2295. https://doi.org/10.1257/aer.103.6.2265

111. Brown, M.E., J.M. Antle, P. Backlund, E.R. Carr, W.E. Easterling, M.K. Walsh, C. Ammann, W. Attavanich, C.B. Barrett, M.F. Bellemare, V. Dancheck, C. Funk, K. Grace, J.S.I. Ingram, H. Jiang, H. Maletta, T. Mata, A. Murray, M. Ngugi, D. Ojima, B. O'Neill, and C. Tebaldi, 2015: Climate Change, Global Food Security, and the U.S. Food System. U.S. Department of Agriculture, 146 pp. https://doi.org/10.7930/j0862dc7

112. Kousky, C. and R. Cooke, 2012: Explaining the failure to insure catastrophic risks. *The Geneva Papers on Risk and Insurance - Issues and Practice*, **37** (2), 206–227. https://doi.org/10.1057/gpp.2012.14

113. Kousky, C., 2022: *Understanding Disaster Insurance: New Tools for a More Resilient Future*. Island Press, Washington, DC, 214 pp. https://islandpress.org/books/understanding-disaster-insurance

114. Kousky, C., 2019: The role of natural disaster insurance in recovery and risk reduction. *Annual Review of Resource Economics*, **11** (1), 399–418. https://doi.org/10.1146/annurev-resource-100518-094028

115. Tack, J., K. Coble, and B. Barnett, 2018: Warming temperatures will likely induce higher premium rates and government outlays for the U.S. crop insurance program. *Agricultural Economics*, **49** (5), 635–647. https://doi.org/10.1111/agec.12448

116. Bansal, R., D. Kiku, and M. Ochoa, 2019: Climate Change Risk. Federal Reserve Bank of San Francisco. https://www.frbsf.org/economic-research/wp-content/uploads/sites/4/paper-5-2019-11-8-kiku-1pm-1st-paper.pdf

117. Alok, S., N. Kumar, and R. Wermers, 2020: Do fund managers misestimate climatic disaster risk. *The Review of Financial Studies*, **33** (3), 1146–1183. https://doi.org/10.1093/rfs/hhz143.

118. Ilhan, E., Z. Sautner, and G. Vilkov, 2021: Carbon tail risk. *The Review of Financial Studies*, **34** (3), 1540–1571. https://doi.org/10.1093/rfs/hhaa071

119. Goldsmith-Pinkham, P.S., M. Gustafson, R. Lewis, and M. Schwert, 2021: Sea Level Rise Exposure and Municipal Bond Yields. Jacobs Levy Equity Management Center for Quantitative Financial Research, 60 pp. https://doi.org/10.2139/ssrn.3478364

120. Engle, R.F., S. Giglio, B. Kelly, H. Lee, and J. Stroebel, 2020: Hedging climate change news. *The Review of Financial Studies*, **33** (3), 1184–1216. https://doi.org/10.1093/rfs/hhz072

121. Krueger, P., Z. Sautner, and L.T. Starks, 2020: The importance of climate risks for institutional investors. *The Review of Financial Studies*, **33** (3), 1067–1111. https://doi.org/10.1093/rfs/hhz137

122. Mueller, J., J. Loomis, and A. González-Cabán, 2009: Do repeated wildfires change homebuyers' demand for homes in high-risk areas? A hedonic analysis of the short and long-term effects of repeated wildfires on house prices in Southern California. *The Journal of Real Estate Finance and Economics*, **38** (2), 155–172. https://doi.org/10.1007/s11146-007-9083-1

123. Hallstrom, D.G. and V.K. Smith, 2005: Market responses to hurricanes. *Journal of Environmental Economics and Management*, **50** (3), 541–561. https://doi.org/10.1016/j.jeem.2005.05.002

124. Hornbeck, R., 2012: The enduring impact of the American Dust Bowl: Short- and long-run adjustments to environmental catastrophe. *American Economic Review*, **102** (4), 1477–1507. https://doi.org/10.1257/aer.102.4.1477

125. Albouy, D., W. Graf, R. Kellogg, and H. Wolff, 2016: Climate amenities, climate change, and American quality of life. *Journal of the Association of Environmental and Resource Economists*, **3** (1), 205–246. https://doi.org/10.1086/684573

126. Druckenmiller, H., 2020: Estimating an Economic and Social Value for Healthy Forests: Evidence from Tree Mortality in the American West. Working Paper. National Science Foundation Graduate Research Fellowship Program. https://static1.squarespace.com/static/5f60e3b9a38e910134a8aeab/t/5fb6df90721aae5081857 9d2/1605820322700/JMP_11.19.2020.pdf

127. Barrage, L., 2020: The fiscal costs of climate change. AEA *Papers and Proceedings*, **110**, 107–112. https://doi.org/10.1257/pandp.20201082

128. CBO, 2021: Budgetary Effects of Climate Change and of Potential Legislative Responses to It. Congressional Budget Office. https://www.cbo.gov/publication/57019

129. Gilmore, E.A., C. Kousky, and T. St.Clair, 2022: Climate change will increase local government fiscal stress in the United States. *Nature Climate Change*, **12** (3), 216–218. https://doi.org/10.1038/s41558-022-01311-x

130. Bakkensen, L. and L. Barrage, 2018: Climate Shocks, Cyclones, and Economic Growth: Bridging the Micro-Macro Gap. Working Paper 24893. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w24893

131. Ortega, F. and S. Taŋpınar, 2018: Rising sea levels and sinking property values: Hurricane Sandy and New York's housing market. *Journal of Urban Economics*, **106**, 81–100. https://doi.org/10.1016/j.jue.2018.06.005

132. CBO, 2016: Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget. Congressional Budget Office, Washington, DC, 46 pp. https://www.cbo.gov/publication/51518

133. DOD, 2021: Department of Defense Climate Risk Analysis. Report Submitted to National Security Council. U.S. Department of Defense, Office of the Undersecretary for Policy, 18 pp. https://media.defense.gov/2021/oct/21/2002877353/-1/-1/0/dod-climate-risk-analysis-final.pdf

134. Baylis, P. and J. Boomhower, 2019: Moral Hazard, Wildfires, and the Economic Incidence of Natural Disasters. Working Paper 26550. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w26550

135. OMB, 2016: Climate Change: The Fiscal Risks Facing the Federal Government. U.S. Office of Management and Budget, 34 pp. https://obamawhitehouse.archives.gov/sites/default/files/omb/reports/omb_climate_change_fiscal_risk_report.pdf

136. Moore, F.C., A. Stokes, M.N. Conte, and X. Dong, 2022: Noah's Ark in a warming world: Climate change, biodiversity loss, and public adaptation costs in the United States. *Journal of the Association of Environmental and Resource Economists*, **9** (5), 981–1015. https://doi.org/10.1086/716662

137. Fann, N., B. Alman, R.A. Broome, G.G. Morgan, F.H. Johnston, G. Pouliot, and A.G. Rappold, 2018: The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012. *Science of The Total Environment*, **610–611**, 802–809. https://doi.org/10.1016/j.scitotenv.2017.08.024

138. Karlsson, M. and N.R. Ziebarth, 2018: Population health effects and health-related costs of extreme temperatures: Comprehensive evidence from Germany. *Journal of Environmental Economics and Management*, **91**, 93–117. https://doi.org/10.1016/j.jeem.2018.06.004

139. Bell, J.E., S.C. Herring, L. Jantarasami, C. Adrianopoli, K. Benedict, K. Conlon, V. Escobar, J. Hess, J. Luvall, C.P. Garcia-Pando, D. Quattrochi, J. Runkle, and C.J. Schreck III, 2016: Ch. 4. Impacts of extreme events on human health. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 99–128. https://doi.org/10.7930/j0bz63zv

140. Ebi, K.L., J.M. Balbus, G. Luber, A. Bole, A. Crimmins, G. Glass, S. Saha, M.M. Shimamoto, J. Trtanj, and J.L. White-Newsome, 2018: Ch. 14. Human health. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 539–571. https://doi.org/10.7930/nca4.2018.ch14

141. Mace, S.E. and A. Sharma, 2020: Hospital evacuations due to disasters in the United States in the twenty-first century. *American Journal of Disaster Medicine*, **15** (1), 7–22. https://doi.org/10.5055/ajdm.2020.0351

142. Watts, N., M. Amann, N. Arnell, S. Ayeb-Karlsson, J. Beagley, K. Belesova, and M. Boykoff, 2021: The 2020 report of the Lancet Countdown on health and climate change: Responding to converging crises. *The Lancet*, **397** (10269), 129–170. https://doi.org/10.1016/s0140-6736(20)32290-x

143. Limaye, V.S., W. Max, J. Constible, and K. Knowlton, 2019: Estimating the health-related costs of 10 climate-sensitive U.S. events during 2012. *GeoHealth*, **3** (9), 245–265. https://doi.org/10.1029/2019gh000202

144. Salas, R.N., T.H. Friend, A. Bernstein, and A.K. Jha, 2020: Adding a climate lens to health policy in the United States. *Health Affairs*, **39** (12), 2063–2070. https://doi.org/10.1377/hlthaff.2020.01352

145. WHO, 2015: Operational Framework for Building Climate Resilient Health Systems. World Health Organization, Geneva, Switzerland, 47 pp. https://apps.who.int/iris/handle/10665/189951

146. Deryugina, T., L. Kawano, and S. Levitt, 2018: The economic impact of Hurricane Katrina on its victims: Evidence from individual tax returns. *American Economic Journal: Applied Economics*, **10** (2), 202–233. https://doi.org/10.1257/app.20160307

147. DeWaard, J., J.E. Johnson, and S.D. Whitaker, 2020: Out-migration from and return migration to Puerto Rico after Hurricane Maria: Evidence from the consumer credit panel. *Population and Environment*, **42** (1), 28–42. https://doi.org/10.1007/s11111-020-00339-5

148. Meléndez, E. and J. Hinojosa, 2017: Estimates of Post-Hurricane Maria Exodus from Puerto Rico. Hunter College, Center for Puerto Rican Studies, New York, NY, 7 pp. https://centropr-archive.hunter.cuny.edu/events-news/rebuild-puerto-rico/policy/estimates-post-hurricane-maria-exodus-puerto-rico

149. Depsky, N., I. Bolliger, D. Allen, J.H. Choi, M. Delgado, M. Greenstone, A. Hamidi, T. Houser, R.E. Kopp, and S. Hsiang, 2022: DSCIM-Coastal v1.0: An open-source modeling platform for global impacts of sea level rise. *EGUsphere*, **2022**, 1–47. https://doi.org/10.5194/egusphere-2022-198

150. Desmet, K., R.E. Kopp, S.A. Kulp, D.K. Nagy, M. Oppenheimer, E. Rossi-Hansberg, and B.H. Strauss, 2021: Evaluating the economic cost of coastal flooding. *American Economic Journal: Macroeconomics*, **13** (2), 444–486. https://doi.org/10.1257/mac.20180366

151. Hauer, M.E., 2017: Migration induced by sea-level rise could reshape the US population landscape. *Nature Climate Change*, **7** (5), 321–325. https://doi.org/10.1038/nclimate3271

152. Puente, G.B., F. Perez, and R.J. Gitter, 2016: The effect of rainfall on migration from Mexico to the United States. *International Migration Review*, **50** (4), 890–909. https://doi.org/10.1111/imre.12116

153. Jones, B.F. and B.A. Olken, 2010: Climate shocks and exports. *American Economic Review*, **100** (2), 454–459. https://doi.org/10.1257/aer.100.2.454

154. Moore, F.C., U. Baldos, T. Hertel, and D. Diaz, 2017: New science of climate change impacts on agriculture implies higher social cost of carbon. *Nature Communications*, **8** (1), 1607. https://doi.org/10.1038/s41467-017-01792-x

155. Dingel, J.I., K.C. Meng, and S.M. Hsiang, 2019: Spatial Correlation, Trade, and Inequality: Evidence from the Global Climate. Working Paper 25447. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w25447

156. Costinot, A., D. Donaldson, and C. Smith, 2016: Evolving comparative advantage and the impact of climate change in agricultural markets: Evidence from 1.7 million fields around the world. *Journal of Political Economy*, **124** (1), 205–248. https://doi.org/10.1086/684719

157. Colacito, R., B. Hoffmann, and T. Phan, 2019: Temperature and growth: A panel analysis of the United States. *Journal of Money, Credit and Banking*, **51** (2–3), 313–368. https://doi.org/10.1111/jmcb.12574

158. IMF, 2017: *Seeking Sustainable Growth: Short-Term Recovery, Long-Term Challenges. World Economic Outlook.* International Monetary Fund, Washington, DC. https://www.imf.org/en/publications/weo/issues/2017/09/19/world-economic-outlook-october-2017

159. Barnett, M., W. Brock, and L.P. Hansen, 2020: Pricing uncertainty induced by climate change. *The Review of Financial Studies*, **33** (3), 1024–1066. https://doi.org/10.1093/rfs/hhz144

160. Hong, H., N. Wang, and J. Yang, 2021: Welfare Consequences of Sustainable Finance. Working Paper 28595. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w28595

161. Olmstead, A.L. and P.W. Rhode, 2011: Adapting North American wheat production to climatic challenges, 1839–2009. *Proceedings of the National Academy of Sciences of the United States of America*, **108** (2), 480–485. https://doi.org/10.1073/pnas.1008279108

162. Roberts, M.J. and W. Schlenker, 2011: Ch. 8. The evolution of heat tolerance of corn: Implications for climate change. In: *The Economics of Climate Change: Adaptations Past and Present*. Libecap, G.D. and R.H. Steckel, Eds. University of Chicago Press, 225–251. http://www.nber.org/chapters/c11988

163. Miao, Q., Y. Hou, and M. Abrigo, 2018: Measuring the financial shocks of natural disasters: A panel study of U.S. states. *National Tax Journal*, **71** (1), 11–44. https://doi.org/10.17310/ntj.2018.1.01

164. EPA, 2017: Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. EPA 430-R-17-001. U.S. Environmental Protection Agency, Washington, DC. https://www.epa.gov/cira/multi-model-framework-quantitative-sectoral-impacts-analysis

165. CPUC, 2018: Order Instituting Rulemaking to Consider Strategies and Guidance for Climate Change Adaptation. Proceeding: R18-04-019. California Public Utilities Commission. https://docs.cpuc.ca.gov/searchres.aspx?docformat=all&docid=213511543

166. Dellink, R., E. Lanzi, and J. Chateau, 2019: The sectoral and regional economic consequences of climate change to 2060. *Environmental and Resource Economics*, **72** (2), 309–363. https://doi.org/10.1007/s10640-017-0197-5

167. Neidell, M., J.G. Zivin, M. Sheahan, J. Willwerth, C. Fant, M. Sarofim, and J. Martinich, 2021: Temperature and work: Time allocated to work under varying climate and labor market conditions. *PLoS ONE*, **16** (8), 0254224. https://doi.org/10.1371/journal.pone.0254224

168. Cohen, F., M. Glachant, and M. Söderberg, 2017: The Cost of Adapting to Climate Change: Evidence from the US Residential Sector. Grantham Research Institute on Climate Change and the Environment Working Paper No. 263; CCCEP Working Paper No. 297. Grantham Research Institute on Climate Change and the Environment, Centre for Climate Change Economics and Policy. https://www.lse.ac.uk/granthaminstitute/publication/the-cost-of-adapting-to-climate-change-evidence-from-the-us-residential-sector/

169. Auffhammer, M., P. Baylis, and C.H. Hausman, 2017: Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (8), 1886–1891. https://doi.org/10.1073/pnas.1613193114

170. Park, R.J., A.P. Behrer, and J. Goodman, 2021: Learning is inhibited by heat exposure, both internationally and within the United States. *Nature Human Behaviour*, **5** (1), 19–27. https://doi.org/10.1038/s41562-020-00959-9

171. Graff Zivin, J., S.M. Hsiang, and M. Neidell, 2018: Temperature and human capital in the short and long run. *Journal of the Association of Environmental and Resource Economists*, **5** (1), 77–105. https://doi.org/10.1086/694177

172. Park, R.J., 2022: Hot temperature and high-stakes performance. *The Journal of Human Resources*, **57** (2), 400–434. https://doi.org/10.3368/jhr.57.2.0618-9535r3

173. Hsiang, S.M., M. Burke, and E. Miguel, 2013: Quantifying the influence of climate on human conflict. *Science*, **341** (6151), 1235367. https://doi.org/10.1126/science.1235367

174. Obradovich, N., R. Migliorini, S.C. Mednick, and J.H. Fowler, 2017: Nighttime temperature and human sleep loss in a changing climate. *Science Advances*, **3** (5), e1601555. https://doi.org/10.1126/sciadv.1601555

175. Obradovich, N., R. Migliorini, M.P. Paulus, and I. Rahwan, 2018: Empirical evidence of mental health risks posed by climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (43), 10953–10958. https://doi.org/10.1073/pnas.1801528115

176. Baylis, P., 2020: Temperature and temperament: Evidence from Twitter. *Journal of Public Economics*, **184**, 104161. https://doi.org/10.1016/j.jpubeco.2020.104161

177. Gellman, J., M. Walls, and M. Wibbenmeyer, 2022: Wildfire, smoke, and outdoor recreation in the western United States. *Forest Policy and Economics*, **134**, 102619. https://doi.org/10.1016/j.forpol.2021.102619

178. Obradovich, N. and J.H. Fowler, 2017: Climate change may alter human physical activity patterns. *Nature Human Behaviour*, **1** (5), 0097. https://doi.org/10.1038/s41562-017-0097

179. Wobus, C., E.E. Small, H. Hosterman, D. Mills, J. Stein, M. Rissing, R. Jones, M. Duckworth, R. Hall, M. Kolian, J. Creason, and J. Martinich, 2017: Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environmental Change*, **45**, 1–14. https://doi.org/10.1016/j.gloenvcha.2017.04.006

180. Fan, Q. and L.A. Bakkensen, 2021: Household sorting as adaptation to hurricane risk in the United States. *Land Economics*, **98** (2), 219–238. https://doi.org/10.3368/le.98.2.111319-0162r1

181. Sinha, P., M.L. Caulkins, and M.L. Cropper, 2018: Household location decisions and the value of climate amenities. *Journal of Environmental Economics and Management*, **92**, 608–637. https://doi.org/10.1016/j.jeem.2017.08.005

182. Kim, H.S., C. Matthes, and T. Phan, 2021: Extreme Weather and the Macroeconomy. Working Paper 21-14R. Federal Reserve Bank of Richmond, 44 pp. https://doi.org/10.21144/wp21-14

183. Kousky, C., E.F.P. Luttmer, and R.J. Zeckhauser, 2006: Private investment and government protection. *Journal of Risk and Uncertainty*, **33** (1), 73–100. https://doi.org/10.1007/s11166-006-0172-y

184. Hsiang, S.M. and A.S. Jina, 2015: Geography, depreciation, and growth. *American Economic Review*, **105** (5), 252–56. https://doi.org/10.1257/aer.p20151029

185. Swart, R., 2019: Assessing physical climate risks for investments: A risky promise. *Climate Services*, **14**, 15–18. https://doi.org/10.1016/j.cliser.2019.04.001

186. TCFD, 2017: Recommendations of the Task Force on Climate-Related Financial Disclosures: Final Report. Task Force on Climate-Related Financial Disclosures. https://assets.bbhub.io/company/sites/60/2020/10/FINAL-2017-TCFD-Report-11052018.pdf

187. Executive Office of the President, 2021: Executive Order 14008: Tackling the climate crisis at home and abroad. *Federal Register*, **86** (19), 7619–7633. https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad

188. Executive Office of the President, 2021: Executive Order 14030: Climate-Related Financial Risk. *Federal Register*, **86**, 27967–27971. https://www.federalregister.gov/documents/2021/05/25/2021-11168/climate-related-financial-risk

189. Frimpong, E., D.R. Petrolia, A. Harri, and J.H. Cartwright, 2020: Flood insurance and claims: The impact of the community rating system. *Applied Economic Perspectives and Policy*, **42** (2), 245–262. https://doi.org/10.1093/aepp/ppz013

190. Garg, T., M. Jagnani, and V. Taraz, 2020: Temperature and human capital in India. *Journal of the Association of Environmental and Resource Economists*, **7** (6), 1113–1150. https://doi.org/10.1086/710066

191. Mullins, J.T. and C. White, 2020: Can access to health care mitigate the effects of temperature on mortality? *Journal of Public Economics*, **191**, 104259. https://doi.org/10.1016/j.jpubeco.2020.104259

192. Baylis, P.W. and J. Boomhower, 2022: Mandated vs. Voluntary Adaptation to Natural Disasters: The Case of U.S. Wildfires. Working Paper 29621. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w29621

193. FEMA, 2020: Building Codes Save: A Nationwide Study. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/2020-11/fema_building-codes-save_study.pdf

194. Simmons, K.M., J. Czajkowski, and J.M. Done, 2018: Economic effectiveness of implementing a statewide building code: The case of Florida. *Land Economics*, **94** (2), 155–174. https://doi.org/10.3368/le.94.2.155

195. Lee, S., 2021: Adapting to Natural Disasters through Better Information: Evidence from the Home Seller Disclosure Requirement. Research Paper No. 21/17. MIT Center for Real Estate. https://doi.org/10.2139/ssrn.3960813

196. Kousky, C., 2018: Financing flood losses: A discussion of the National Flood Insurance Program. *Risk Management and Insurance Review*, **21** (1), 11–32. https://doi.org/10.1111/rmir.12090

197. Gallagher, J. and D. Hartley, 2017: Household finance after a natural disaster: The case of Hurricane Katrina. *American Economic Journal: Economic Policy*, **9** (3), 199–228. https://doi.org/10.1257/pol.20140273

198. Phan, T. and F.F. Schwartzman, 2023: Climate Defaults and Financial Adaptation. Working Paper No. 23-06. Federal Reserve Bank of Richmond. https://doi.org/10.21144/wp23-06

199. Annan, F. and W. Schlenker, 2015: Federal crop insurance and the disincentive to adapt to extreme heat. *American Economic Review*, **105** (5), 262–266. https://doi.org/10.1257/aer.p20151031

200. National Academies of Sciences, Engineering, and Medicine, 2017: *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. The National Academies Press, Washington, DC, 280 pp. https://doi.org/10.17226/24651

201. IWG, 2021: Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide—Interim Estimates under Executive Order 13990. U.S. Government, Interagency Working Group on Social Cost of Greenhouse Gases. https://www.whitehouse.gov/wp-content/uploads/2021/02/technicalsupportdocument_socialcostofcarbonmethanenitrousoxide.pdf

202. Brunetti, C., B. Dennis, D. Gates, D. Hancock, D. Ignell, E.K. Kiser, G. Kotta, A. Kovner, R.J. Rosen, and N.K. Tabor, 2021: Climate Change and Financial Stability. FEDS Notes. Board of Governors of the Federal Reserve System, Washington, DC. https://doi.org/10.17016/2380-7172.2893

203. FSOC, 2021: Report on Climate-Related Financial Risk. Financial Stability Oversight Council, Washington, DC. https://home.treasury.gov/system/files/261/FSOC-Climate-Report.pdf

204. Hansen, L.P., 2022: Central banking challenges posed by uncertain climate change and natural disasters. *Journal of Monetary Economics*, **125**, 1–15. https://doi.org/10.1016/j.jmoneco.2021.09.010

205. Jung, H., R. Engle, and R. Berner, 2021: CRISK: Measuring the Climate Risk Exposure of the Financial System. FRB of New York Staff Report No. 977. Federal Reserve Bank of New York. https://www.newyorkfed.org/medialibrary/media/research/staff_reports/sr977.pdf

206. Phan, T., 2021: Climate Change and Financial Stability? Recalling Lessons from the Great Recession. Economic Brief No. 21-27. Federal Reserve Bank of Richmond. https://www.richmondfed.org/publications/research/economic_brief/2021/eb_21-27

207. Climate-Related Market Risk Subcommittee, 2020: Managing Climate Risk in the U.S. Financial System. U.S. Commodity Futures Trading Commission, Market Risk Advisory Committee, Washington, DC, 165 pp. https://www.preventionweb.net/quick/50716

208. Bakkensen, L.A., T. Phan, and T.-N. Wong, 2023: Leveraging the Disagreement on Climate Change: Theory and Evidence. Working Paper No. 23-01. Federal Reserve Bank of Richmond. https://doi.org/10.21144/wp23-01

209. Ouazad, A. and M.E. Kahn, 2022: Mortgage finance and climate change: Securitization dynamics in the aftermath of natural disasters. *The Review of Financial Studies*, **35** (8), 3617–3665. https://doi.org/10.1093/rfs/hhab124

210. Phan, T., 2022: Are Some Homebuyers Strategically Transferring Climate Risks to Lenders? Economic Brief, No. 22-14. Federal Reserve Bank of Richmond. https://www.richmondfed.org/publications/research/economic_brief/2022/eb_22-14

211. Murfin, J. and M. Spiegel, 2020: Is the risk of sea level rise capitalized in residential real estate? *The Review of Financial Studies*, **33** (3), 1217–1255. https://doi.org/10.1093/rfs/hhz134

212. Heyes, A. and S. Saberian, 2019: Temperature and decisions: Evidence from 207,000 court cases. *American Economic Journal: Applied Economics*, **11** (2), 238–265. https://doi.org/10.1257/app.20170223

213. Obradovich, N., 2017: Climate change may speed democratic turnover. *Climatic Change*, **140** (2), 135–147. https://doi.org/10.1007/s10584-016-1833-8

214. Burke, M., S.M. Hsiang, and E. Miguel, 2015: Climate and conflict. *Annual Review of Economics*, **7** (1), 577–617. https://doi.org/10.1146/annurev-economics-080614-115430

215. Ranson, M., 2014: Crime, weather, and climate change. *Journal of Environmental Economics and Management*, **67** (3), 274–302. https://doi.org/10.1016/j.jeem.2013.11.008

216. Du, D. and X. Zhao, 2020: Hurricanes and Residential Mortgage Loan Performance. WP-2020-04. U.S. Department of the Treasury, Office of the Comptroller of the Currency, 48 pp. https://www.occ.gov/publications-and-resources/publications/economics/working-papers-banking-perf-reg/economic-working-paper-hurricanes-residential-mortgage-loan-perf.html

217. Kunreuther, H.C. and E.O. Michel-Kerjan, 2011: *At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes*. MIT Press, 440 pp. https://mitpress.mit.edu/9780262516549/at-war-with-the-weather/

218. Healy, A. and N. Malhotra, 2010: Random events, economic losses, and retrospective voting: Implications for democratic competence. *Quarterly Journal of Political Science*, **5** (2), 193–208. https://doi.org/10.1561/100.00009057

219. Acosta, R.J., N. Kishore, R.A. Irizarry, and C.O. Buckee, 2020: Quantifying the dynamics of migration after Hurricane Maria in Puerto Rico. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (51), 32772–32778. https://doi.org/10.1073/pnas.2001671117

220. Cattaneo, C., M. Beine, C.J. Fröhlich, D. Kniveton, I. Martinez-Zarzoso, M. Mastrorillo, K. Millock, E. Piguet, and B. Schraven, 2019: Human migration in the era of climate change. *Review of Environmental Economics and Policy*, **13** (2), 189–206. https://doi.org/10.1093/reep/rez008

221. Cai, R., S. Feng, M. Oppenheimer, and M. Pytlikova, 2016: Climate variability and international migration: The importance of the agricultural linkage. *Journal of Environmental Economics and Management*, **79**, 135–151. https://doi.org/10.1016/j.jeem.2016.06.005

222. Missirian, A. and W. Schlenker, 2017: Asylum applications respond to temperature fluctuations. *Science*, **358** (6370), 1610–1614. https://doi.org/10.1126/science.aao0432

223. Belasen, A.R. and S.W. Polachek, 2008: How hurricanes affect wages and employment in local labor markets. *The American Economic Review*, **98** (2), 49–53. http://www.jstor.org/stable/29729993

224. Kousky, C., B. Lingle, and L. Shabman, 2017: The pricing of flood insurance. *Journal of Extreme Events*, **4** (2), 1750001. https://doi.org/10.1142/s2345737617500014

225. Auffhammer, M. and A. Aroonruengsawat, 2011: Simulating the impacts of climate change, prices and population on California's residential electricity consumption. *Climatic Change*, **109** (1), 191–210. https://doi.org/10.1007/s10584-011-0299-y

226. Butler, E.E. and P. Huybers, 2013: Adaptation of US maize to temperature variations. *Nature Climate Change*, **3**, 68–72. https://doi.org/10.1038/nclimate1585

227. Lorie, M., J.E. Neumann, M.C. Sarofim, R. Jones, R.M. Horton, R.E. Kopp, C. Fant, C. Wobus, J. Martinich, M. O'Grady, and L.E. Gentile, 2020: Modeling coastal flood risk and adaptation response under future climate conditions. *Climate Risk Management*, **29**, 100233. https://doi.org/10.1016/j.crm.2020.100233

228. Howard, P.H. and T. Sterner, 2017: Few and not so far between: A meta-analysis of climate damage estimates. *Environmental and Resource Economics*, **68** (1), 197–225. https://doi.org/10.1007/s10640-017-0166-z

229. Dietz, S., J. Rising, T. Stoerk, and G. Wagner, 2021: Economic impacts of tipping points in the climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (34), e2103081118. https://doi.org/10.1073/pnas.2103081118

230. Kemp, L., C. Xu, J. Depledge, K.L. Ebi, G. Gibbins, T.A. Kohler, J. Rockström, M. Scheffer, H.J. Schellnhuber, W. Steffen, and T.M. Lenton, 2022: Climate endgame: Exploring catastrophic climate change scenarios. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (34), e2108146119. https://doi.org/10.1073/pnas.2108146119

231. Nordhaus, W., 2019: Economics of the disintegration of the Greenland ice sheet. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (25), 12261–12269. https://doi.org/10.1073/pnas.1814990116

232. Dietz, S., J. Rising, T. Stoerk, and G. Wagner, 2022: Reply to Keen et al.: Dietz et al. modeling of climate tipping points is informative even if estimates are a probable lower bound. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (21), e2201191119. https://doi.org/10.1073/pnas.2201191119

233. Keen, S., T.M. Lenton, T.J. Garrett, J.W.B. Rae, B.P. Hanley, and M. Grasselli, 2022: Estimates of economic and environmental damages from tipping points cannot be reconciled with the scientific literature. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (21), e2117308119. https://doi.org/10.1073/pnas.2117308119

234. Giglio, S., B. Kelly, and J. Stroebel, 2021: Climate finance. *Annual Review of Financial Economics*, **13** (1), 15–36. https://doi.org/10.1146/annurev-financial-102620-103311

235. Alman, B.L., G. Pfister, H. Hao, J. Stowell, X. Hu, Y. Liu, and M.J. Strickland, 2016: The association of wildfire smoke with respiratory and cardiovascular emergency department visits in Colorado in 2012: A case crossover study. *Environmental Health*, **15** (1), 64. https://doi.org/10.1186/s12940-016-0146-8

236. Gan, R.W., B. Ford, W. Lassman, G. Pfister, A. Vaidyanathan, E. Fischer, J. Volckens, J.R. Pierce, and S. Magzamen, 2017: Comparison of wildfire smoke estimation methods and associations with cardiopulmonary-related hospital admissions. *GeoHealth*, **1** (3), 122–136. https://doi.org/10.1002/2017gh000073

237. Miller, N., D. Molitor, and E. Zou, 2017: Blowing Smoke: Health Impacts of Wildfire Plume Dynamics. University of Illinois, 35 pp. https://nmiller.web.illinois.edu//documents/research/smoke.pdf

238. Issler, P., R. Stanton, C. Vergara-Alert, and N. Wallace, 2020: Mortgage Markets with Climate-Change Risk: Evidence from Wildfires in California. Social Science Research Network, 48 pp. https://doi.org/10.2139/ssrn.3511843

239. Netusil, N.R., C. Kousky, S. Neupane, W. Daniel, and H. Kunreuther, 2021: The willingness to pay for flood insurance. *Land Economics*, **97** (1), 17–38. https://doi.org/10.3368/wple.97.1.110819-0160r1

240. GAO, 2021: FEMA Flood Maps: Better Planning and Analysis Needed to Address Current and Future Flood Hazards. GAO-22-104079. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-22-104079.pdf

241. Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous, 2012: The environment and directed technical change. *American Economic Review*, **102** (1), 131–66. https://doi.org/10.1257/aer.102.1.131

242. Kompas, T., V.H. Pham, and T.N. Che, 2018: The effects of climate change on GDP by country and the global economic gains from complying with the Paris Climate Accord. *Earth's Future*, **6** (8), 1153–1173. https://doi.org/10.1029/2018ef000922

243. Nordhaus, W.D., 2017: Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (7), 1518–1523. https://doi.org/10.1073/pnas.1609244114

244. Roson, R. and M. Sartori, 2016: Estimation of climate change damage functions for 140 regions in the GTAP 9 Data Base. *Journal of Global Economic Analysis*, **1** (2), 78–115. https://doi.org/10.21642/jgea.010202af

245. Collier, B., L. Powell, M.A. Ragin, and X. You, 2020: Financing Negative Shocks: Evidence from Hurricane Harvey. Social Science Research Network. https://doi.org/10.2139/ssrn.3741812

246. Collier, B.L., A.F. Haughwout, H.C. Kunreuther, and E.O. Michel-Kerjan, 2020: Firms' management of infrequent shocks. *Journal of Money, Credit and Banking*, **52** (6), 1329–1359. https://doi.org/10.1111/jmcb.12674

247. Davlasheridze, M., K. Fisher-Vanden, and H.A. Klaiber, 2017: The effects of adaptation measures on hurricane induced property losses: Which FEMA investments have the highest returns? *Journal of Environmental Economics and Management*, **81**, 93–114. https://doi.org/10.1016/j.jeem.2016.09.005

248. Kousky, C. and E. Michel-Kerjan, 2017: Examining flood insurance claims in the United States: Six key findings. *Journal of Risk and Insurance*, **84** (3), 819–850. https://doi.org/10.1111/jori.12106

249. Wagner, K.R.H., 2022: Adaptation and adverse selection in markets for natural disaster insurance. *American Economic Journal: Economic Policy*, **14** (3), 380–421. https://doi.org/10.1257/pol.20200378

250. Pope, J.C., 2008: Do seller disclosures affect property values? Buyer information and the hedonic model. *Land Economics*, **84** (4), 551–572. https://doi.org/10.3368/le.84.4.551

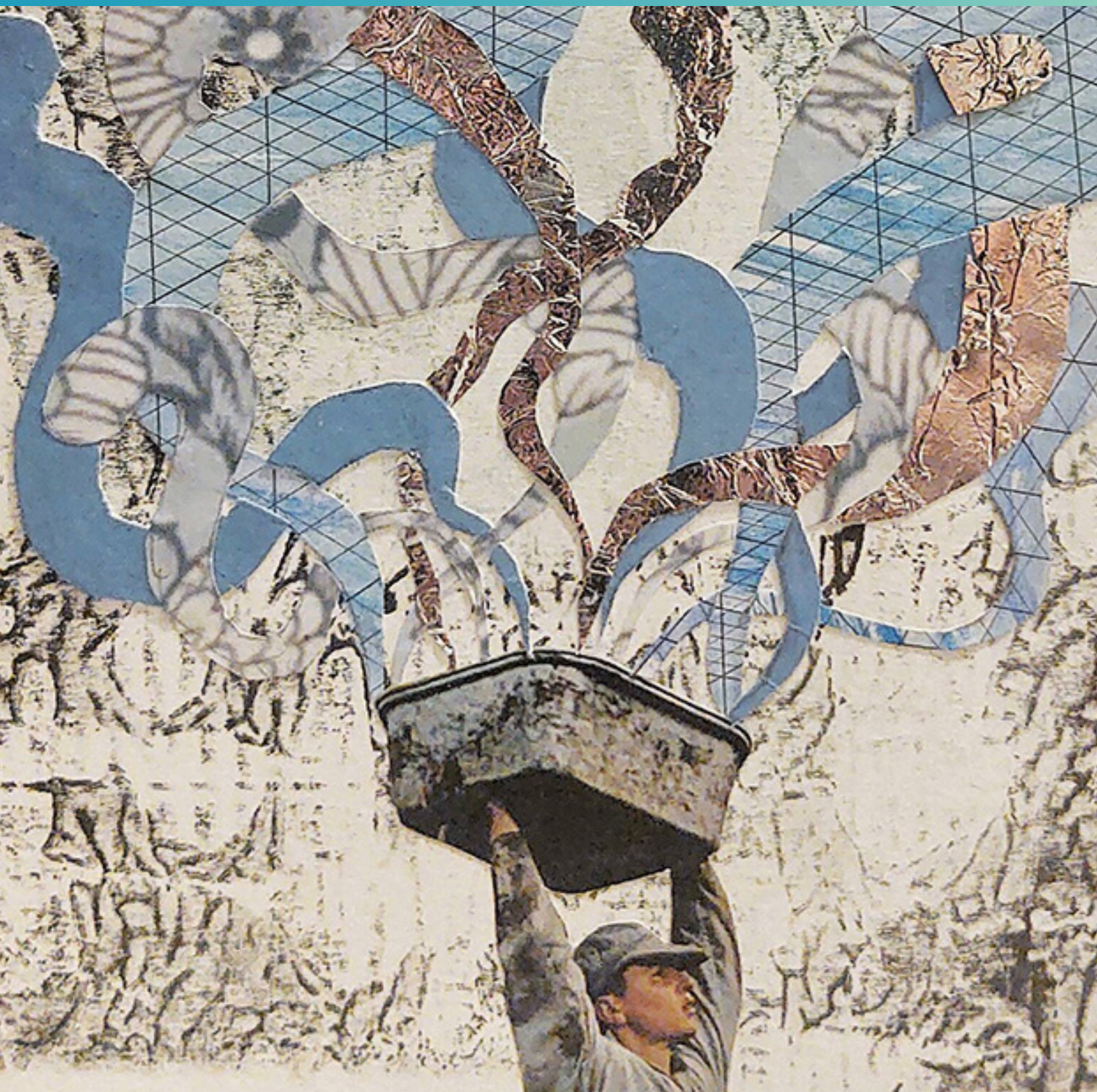
251. Kousky, C., H. Kunreuther, B. Lingle, and L. Shabman, 2018: The Emerging Private Residential Flood Insurance Market in the United States. University of Pennsylvania, Wharton Risk Management and Decision Processes Center, 53 pp. https://www.preventionweb.net/quick/47371

252. Auffhammer, M. and J.R. Vincent, 2012: Unobserved time effects confound the identification of climate change impacts. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (30), 11973-11974. https://doi.org/10.1073/pnas.1202049109

253. Feng, S. and M. Oppenheimer, 2012: Applying statistical models to the climate–migration relationship. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (43), E2915-E2915. https://doi.org/10.1073/pnas.1212226109

Fifth National Climate Assessment: Chapter 20

# Social Systems and Justice



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# Introduction

## *Social Systems Are Where Climate Change Is Created and Experienced*

Climate change is a result of human behavior and has differentiated effects on communities and peoples around the United States and the globe. It is inextricably tied to a history of human development and decision-making—from individuals to organizations to entire societies. For this reason, we cannot fully understand or respond to current or future changes in climate without understanding this history of human organization—that is, without understanding social systems.

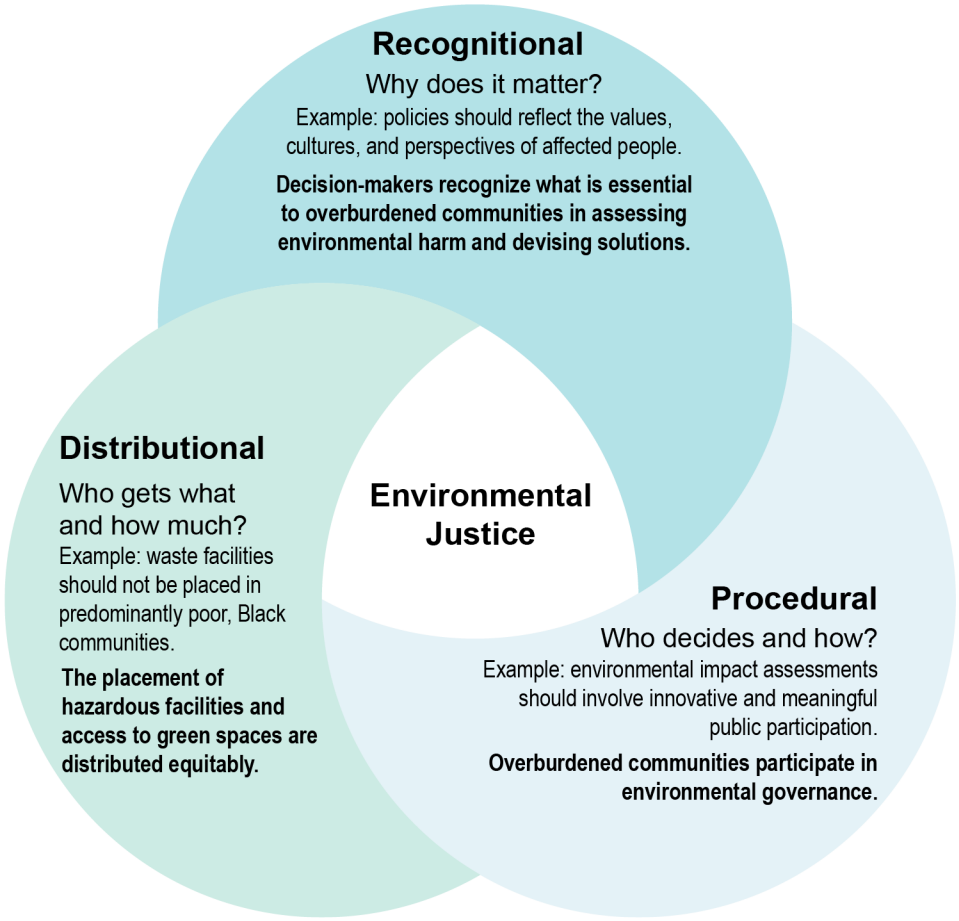
Social systems create and reproduce the assumptions that we—individuals and institutions—act on when making decisions about climate change over time and space. This might include what a given community considers sacred or taboo, or how we speak of and conceptualize environmental problems. Lack of rain, for example, may be conceptualized differently by scientists, farmers, government agencies, and land developers; and what is identified as cause for action (or sacrifice) may change depending on whether growing food is experienced as sacred, a national security issue, or an economic input.

Critically, social systems define who is seen as deserving of local, state, and federal interventions to address climate impacts. For example, they determine which neighborhoods receive hazard mitigation investment or post-disaster recovery aid. Through complex interactions, conscious and unconscious tendencies and biases, and visible and invisible social rules, social systems distribute climate risks and benefits; they also create the opportunities for climate adaptations and climate mitigation to be envisioned and acted upon.

There is growing evidence that understanding social systems is an integral part of climate science and climate solutions-making, including identifying links among adaptation, mitigation, and climate justice. The importance of social science and humanities research on climate change has been made clear by contributions across many fields, including but not limited to anthropology, communication, ethnic studies, geography, history, linguistics, philosophy, political science, psychology, public policy and administration, religious studies, and sociology.

This chapter highlights and summarizes contributions to climate change science from across the social sciences. It explains that social systems give rise to greenhouse gas emissions and distribute the risks and benefits of industrialization and climate change (KM 20.1). The chapter also explains how knowledge, culture, ethics, communication, and decision-making shape engagement with and responses to climate change (KM 20.2), as well as how climate adaptation and mitigation processes, such as human migration and transitions away from fossil fuels, may be just or unjust (KM 20.3). Central to this chapter is an explanation of how social systems inequitably distribute harm to BIPOC (Black, Indigenous, and People of Color), low-income, and rural communities; women and gender minorities; and other racialized or overburdened peoples. Key to this explanation are the concepts of environmental justice and environmental injustice. Environmental justice has three primary dimensions: recognitional, distributional, and procedural (Figure 20.1). This chapter uses these three dimensions to explore whether the actions taken to create, mitigate, or adapt to climate change are expected to produce just or unjust outcomes.

## Three Dimensions of Environmental Justice




**Environmental justice requires three dimensions: recognitional, distributional, and procedural justice.**

**Figure 20.1.** These three dimensions of justice are based on a framework originally summarized by the "father of environmental justice," Robert Bullard,[1] who pointed to the "ethical and political questions of 'who gets what, why, and in what amounts?'" Commitments to each dimension are essential to achieving environmental justice, and each dimension can influence the others.[2,3,4] Figure credit: Puget Sound Partnership, Citizen Potawatomi Nation, and University of Michigan.

## Key Message 20.1

## Social Systems Are Changing the Climate and Distributing Its Impacts Inequitably

Social systems are changing the climate (*very high confidence*). Societal characteristics and processes shape greenhouse gas (GHG) emissions, primarily through the burning of fossil fuels (*very high confidence*). Social systems also inequitably distribute the benefits of energy consumption and the impacts of GHG emissions and climate change (*high confidence*). Governance is a critical process that distributes these impacts (*very high confidence*) and provides access to adaptation (*medium confidence*).

### *Emissions Are a Consequence of Social Systems*

Social systems produce and distribute climate change and its impacts through mechanisms such as economic growth, population dynamics, social and economic inequities, governance, militarization, and world-economic integration (KM 2.1).[5,6,7,8] Greenhouse gas (GHG) emissions, and especially carbon emissions, are a significant and measurable outcome of energy use that leads directly to climate change (KM 3.1), the impacts of which are largely determined by social systems.[9,10,11,12] The relationships between emissions and standards of living in higher-income and lower-income nations exemplify unequal access to the benefits of industrialization and world-economic integration[13,14,15,16,17] and highlight different responsibilities for the human drivers of climate change.[17,18,19,20] Industrial processes over the past two centuries produced GHG emissions and improved quality of life, but these benefits have not been equitably distributed.[21,22,23,24] However, some societies (e.g., countries or smaller subnational units) have achieved high levels of human well-being, such as increased average life expectancy or perceived high quality of life, without consuming substantial amounts of fossil fuels per capita.[25,26,27,28,29,30,31,32,33]

Relationships between emissions and other social features are evident across time and space and at different scales. National-level carbon emissions are strongly associated with economic growth.[34,35,36,37,38,39,40,41] Using regression analysis, researchers have also identified structural factors that shape the relationship between economic growth and carbon emissions. For example, the relationship between emissions and economic growth is stronger for nations with greater levels of income and wealth inequality or whose economies are more reliant on natural resource exports.[42,43,44,45,46,47] All else being equal, nations with larger and more capital-intensive militaries have higher emissions,[48,49,50,51] most notably the United States.[52,53,54] Conversely, nations with a stronger environmental civil society or more gender equality experience a decrease in the relationship between economic growth and emissions.[55,56,57]

Carbon emissions, overall, have a positive association with population size.[39,58,59,60] Population growth is higher in lower-income nations than in higher-income nations and contributes to rising energy consumption and carbon emissions, although empirical research also suggests that such population growth threatens global climate stability less than higher-income nations' carbon-intensive economic activities.[61,62]

Subnational analyses show that increases in emissions over time are moderately lower in US states with a greater concentration of environmental nongovernmental organizations[63] and in US states with legislators exhibiting strong environmental records.[64] This research points to the role of governance and related institutional arrangements in mitigating emissions.

## Climate Impacts Are Distributed Unevenly

While all people are exposed to human-caused climate change stemming from GHG emissions, social systems shape the degree of exposure and distribute climate impacts across people and places over time (KMs 4.2, 5.2, 11.2, 15.2, 23.1, 31.2). *Exposure* and *impact* are differentiated in the social science and climate change literature. As an example, flood exposure is understood as the probability of water inundation and risk to infrastructure, whereas flood impacts could be the displacement and housing insecurity that result from preexisting conditions interacting with the inundation or high water.[65] Individuals and communities that have lived at the margins of, or have been purposely excluded from the benefits of, industrialization have a greater probability of exposure to pollution and negative environmental impacts.[66] For example, in the United States, Black and BIPOC individuals and communities, members of low-income households, immigrants with limited English proficiency, unhoused individuals,[67,68,69] rural communities,[70,71,72,73] and agricultural workers are disproportionately impacted by environmental hazards[66,74] and climate change (Figures 4.15, 4.16, 18.2; KMs 4.2, 11.2, 14.3, 15.2). The convergence of exclusion, exposure, and impacts places unequal burdens on these individuals and communities, sometimes referred to as overburdened communities.

The burdens of climate change and social inequity become acute during disaster events[71,75,76,77,78,79] and can be exacerbated by governance decisions.[80] Hurricanes Maria and Harvey, for example, had disproportionate impacts on minority households, renters, multifamily households, and low-income families due in part to governance decisions related to aid distribution and documentation requirements (Box 4.2; KMs 23.1, 23.5; Figure 26.3). In this case, application and appeals processes for disaster assistance required documentation that some residents did not have or required the navigation of complex aid structures that some people could not successfully find their way through.[81] This left those same families and communities struggling to meet basic needs in the immediate aftermath[82,83] and unable to access funding for rebuilding. These obstacles to recovery can have long-term generational effects related to the loss of savings, housing insecurity, and displacement. For example, people who migrated to California from the southern Midwest during the Great Depression fared worse than native Californians for at least a generation.[84] The absence of data and data collection, such as demographic and hazard data, compounds the challenges of equitable governance during disasters. Data limitations in territories, for example, have direct impacts on the availability of resources and the visibility of at-risk populations.[85,86,87]

Policy processes and governance also influence the formation of socioecological landscapes before and after climate change–related disasters.[88,89,90] For example, the use of a cost–benefit analysis for the allocation of hazard mitigation funding, and disaster-related assistance for rebuilding, gives priority to areas of denser population and higher-value housing stock.[91] Pre-event social vulnerabilities, such as a lack of clear title for real estate, lack of financial capital, and subpar housing leave some populations at greater risk of negative impacts following a disaster.[81] For example, a family without clear title may have a more difficult time proving home ownership in order to access federal rebuilding assistance, and subpar housing may be more difficult to insure and repair.

## Structural Inequalities Affect Outcomes

Even when all citizens are treated the same under the law, differential outcomes may result if the law ignores structural inequalities.[92,93] For example, when aid is delayed or not readily available following a disaster, low-income individuals and families may lack access to food and shelter even when those costs will be reimbursed. Under these same conditions, middle- or high-income individuals and families often have greater access to credit and other financial resources that allow them to spend money now and then wait for reimbursement.[94]

All levels of government (including federal, state, and county) shape the impacts of climate change and are impacted by a complex variety of social systems (Figure 20.2). Inclusive, rapid governance responses

that promote adaptation and mitigation are challenging to create,[95,96] in part because governmental institutions have difficulty innovating quickly.[97] Conditions that create the disaster impacts described above occur over decades or centuries, while governance responses to these impacts are asked to be created in far less time in order to be effective. The United States' three-branch system of government was designed to prevent those in power from taking quick action and harming those in the minority.[98] Stemming from this arrangement, a key challenge for climate adaptation and mitigation is how to react to quickly changing circumstances given the slow pace at which legislative action and other forms of governance occur (KMs 4.3, 31.3).

## Climate Change Governance

**Climate change governance is complex and multifaceted.**

**Figure 20.2.** This figure recognizes the complex interaction of multiple social systems that give rise to governance. Climate change impacts, and the impacts of adaptation and mitigation strategies, will all be mediated by governance decisions and actions. Understanding this complex interplay allows the social scientists who study climate change to make predictions regarding climate impacts and to assess where governance systems are expected to produce climate justice or injustice. Figure credit: Jacksonville State University.

One example of adaptive governance in the face of climate risk occurred in Tulsa, Oklahoma, where a broad coalition of civil society and local, state, and federal government actors came together to address flood risk and to create structures and organizations that continue to drive risk reduction for all hazards. Tulsa was the most frequently flooded city in the United States from the 1960s through the 1980s.[99] Almost 40 years ago, a coalition of concerned citizens and flood victims brought pressure to bear on city hall to address the problem. This coalition was eventually joined by government and elected officials and supported by federal partners, which led to a comprehensive floodplain management approach that has served as a model for other cities.[100] The city was able to enact stricter land-use regulations and draw on federal incentives through the Community Rating System to garner public and political support.[101]

## Key Message 20.2

## Social Systems Structure How People Know and Communicate About Climate Change

People's histories, educations, cultures, and ethics determine how they understand and experience climate change (*high confidence*). These knowledges take multiple forms (*high confidence*) and generate diverse approaches to climate adaptation and mitigation (*medium confidence*). Engagement across communities that builds clear objectives and benchmarks has been shown to produce more desired outcomes (*medium confidence*). Effective engagement is challenging due in part to the complexity and uncertainty associated with climate science and politics (*high confidence*). Including community perspectives and multiple forms of knowledge in climate discussions and decision-making helps promote justice (*medium confidence*).

### *How People Know About Climate Change*

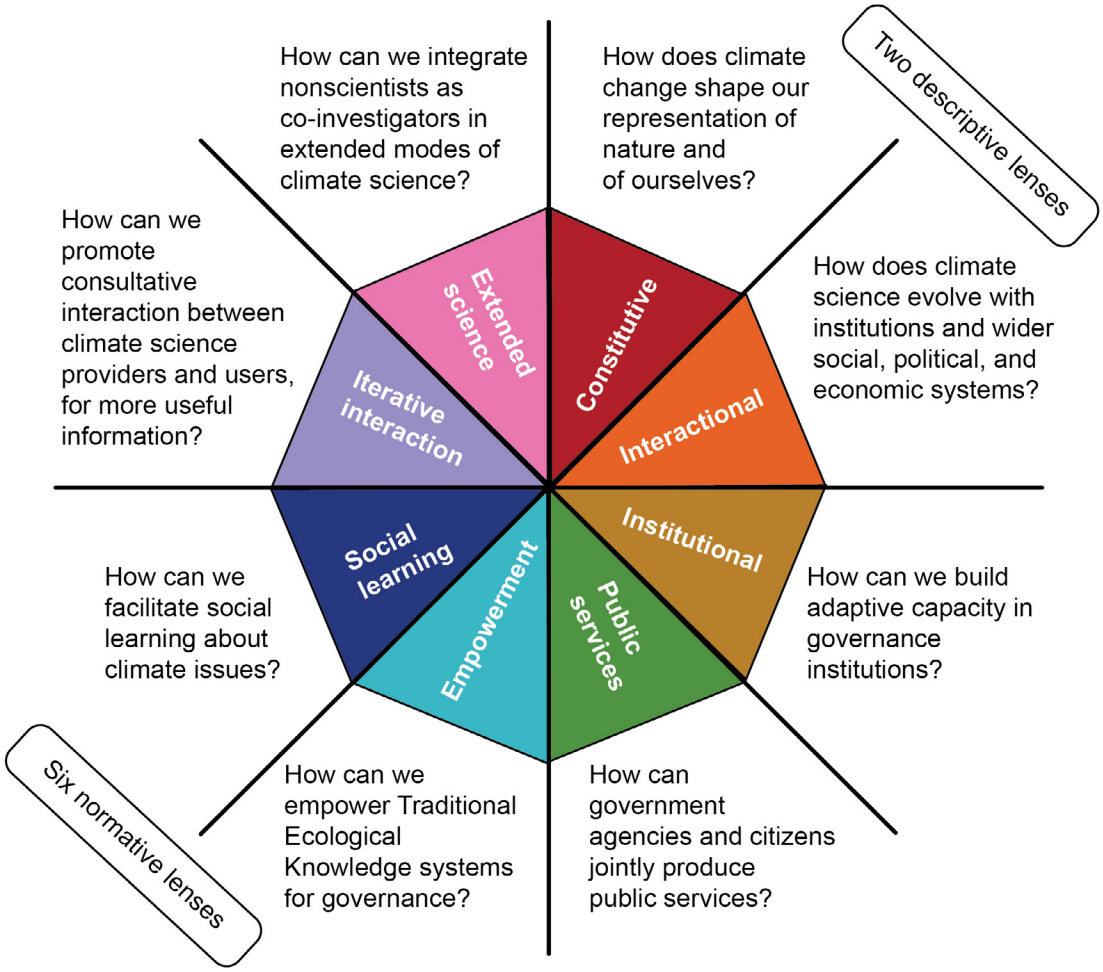
Researchers in the social sciences and humanities have studied the ways in which people and groups learn about and understand human–nature interactions, including climate change.[102,103,104] Epistemology is the name for the study of how people develop knowledge. For both scientists and nonscientists, epistemological assumptions influence an understanding of what the drivers of climate change are, what kinds of evidence matter, and what are seen as appropriate and ethical responses to its risks and impacts.[105,106,107,108,109,110,111,112] For example, climate modelers may use computer models to predict the thinning and reduction of Arctic Sea ice in order to produce more accurate maps and forecasts. Indigenous Arctic walrus hunters might instead draw on their experiences and observations to better understand the complex interconnections among ice thickness and timing, ocean currents, walrus behavior, prey dynamics, accessibility of hunting locations, travel safety, and food security to make decisions about the long-term sustainability and health of their community,[113] which may conceptually include both walruses and people.

Recognizing that knowledge emerges out of different histories and traditions can lead to new insights regarding mitigation and adaptation (Box 23.1).[114,115,116,117,118,119,120] For climate scientists, the principal driver of climate change is understood to be GHG emissions.[121] From this perspective, climate mitigation involves reducing emissions. In contrast, people who have been excluded from the benefits of industrialization, or disproportionately harmed by industrial processes, might see the principal driver of climate change as the social systems and ethical arrangements that allowed for the simultaneous exploitation of land, animals, and peoples.[77,119,122,123,124,125,126,127,128] If climate change is understood as an outcome of socioeconomic and ethical arrangements that resulted in exploitation and discrimination, then reexamining those arrangements also

becomes necessary.[129,130,131,132,133,134,135] Most often these insights are not contradictory but rather expand the universe of possible solutions for climate adaptation and mitigation.[136,137]

A promising area of research that takes different forms of knowledge seriously is called coproduced or cocreated research (Figure 20.3).[138,139,140] While coproduction is an increasingly widely used term with varied definitions (Figure 20.3), coproduced climate change research projects often integrate community-based insights and solutions to climate change with scientific insights and solutions. Coproduced research often foregrounds nonscientists, such as Indigenous Knowledge holders or multigenerational farming communities, as experts within their own knowledge contexts (KMs 18.3, 31.5). This kind of research can give rise to community-based resilience efforts. Research in the Arctic, for example, has been particularly successful at experimenting with coproduction, especially in integrating Indigenous and Western scientific knowledge bases.[141,142] However, integration can fail if power dynamics, goals, trust, and compensation within research teams and epistemologies are not equitable.[143]

## Coproduction in Research




**Coproduction is a way forward to include multiple epistemologies, or knowledge traditions, but must be defined to be productive.**

**Figure 20.3.** This figure demonstrates the diverse approaches to coproduction and focuses on the need to define what a research team means when seeking to do a coproduced research project. The two items in the top right quadrant are descriptive lenses, while the other six are normative lenses. Adapted with permission from Bremer and Meisch 2017.[138]

One important consequence of different epistemological assumptions is that different people and groups perceive climate change risks and possible solutions in widely different, often compatible, but sometimes conflicting, ways.[144,145] For example, the politicization of climate change in the US helps to explain differences in public perceptions of severity and concern as a function of demographic factors such as gender and political ideology.[146,147] In this case, women and liberal-identifying individuals report relatively higher levels of concern and support for mitigative action and policy. In contrast, climate change is a relatively less polarizing issue among racial and ethnic minorities as well as socioeconomically disadvantaged groups compared to White populations and higher-income groups.[148] In part, beliefs and concerns about climate change have been shaped by well-documented, intentional efforts by industry groups supportive of the continued use and promotion of fossil fuels to misrepresent the uncertainty and knowledge about climate change and downplay the risks to society.[149,150,151,152]

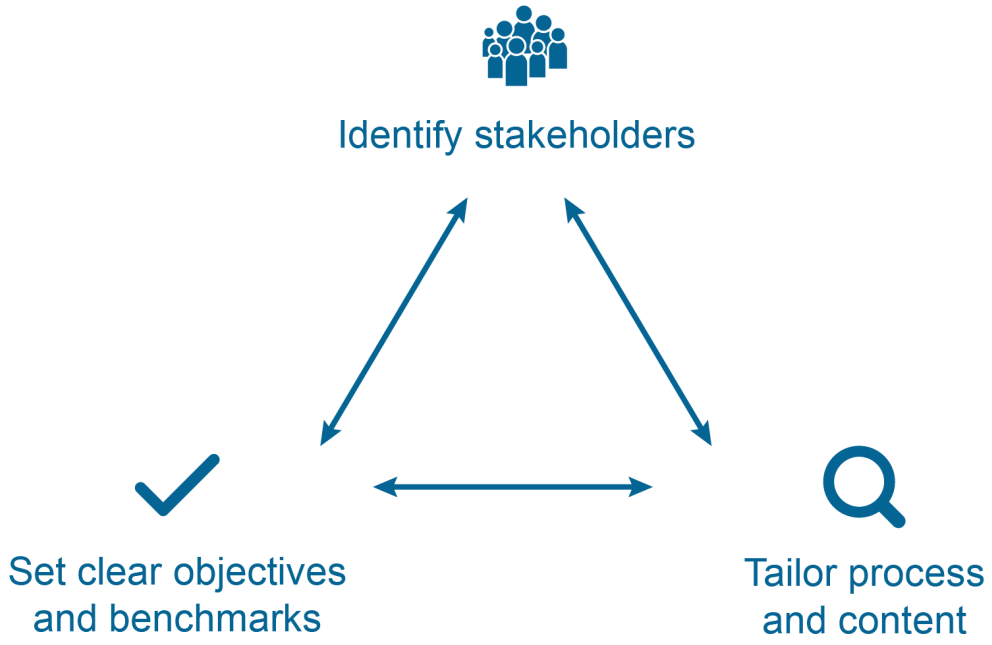
## *Processes for Promoting More Effective Climate Change Engagement Efforts*

As suggested above, diverse communities have distinct knowledge traditions within which people interpret climate change. These diverse communities also engage with climate science and information in different social and cultural settings. There have been numerous explicit efforts over the past few decades to build greater levels of public engagement with the issue of climate change and climate science. These climate change engagement efforts have taken many forms, including traditional expert-to-public communication products (e.g., USGCRP National Climate Assessments, documentaries, journalism) and more participatory activities (e.g., public art installations, town meetings, deliberative democracy forums).[153] These efforts occur in both formal (e.g., K–12 and college classrooms) and informal (e.g., zoos, museums) settings and are sometimes tied to intentional educational activities; however, much climate change engagement occurs outside formal classroom settings.

Significant efforts and resources have been put into improving the effectiveness and accessibility of climate change information and engagement activities over the past decade. One outcome of these efforts has been collective learning regarding processes and actions that improve effectiveness of climate change engagement efforts. We describe some of these insights below.

First, establishing clear, measurable objectives with well-defined benchmarks or desired outcomes leads to more effective communication products and processes (Figure 20.4); bringing key stakeholders into the process at this early stage can improve effectiveness.

## Successful Climate Engagement




**A simple three-step process of communication can improve climate change engagement with diverse stakeholders.**

**Figure 20.4.** Simple changes can help facilitate communication about climate change. Identifying the stakeholders, tailoring the process of communication and knowledge creation, and setting clear objectives for everyone involved has been shown to be an effective process. Figure credit: Rutgers University, University of Massachusetts Amherst, and Oregon State University–Cascades.

Second, to inform real-world decision-making, information needs to be calibrated to the needs of target audiences;[154,155] importantly, communicating relevant information sometimes involves translating science into accessible and actionable language, whereas in other cases it involves incorporating diverse forms of knowledge into communications products and efforts. For example, farmers and forest owners often have different informational needs with respect to climate change impacts and implications for management: whereas farmers may be most interested in seasonal forecasts or timescales of a few years, forest owners may be more interested in projections of trends for the next few decades. Climate change communicators must know—or put in place processes to uncover—the needs and epistemologies of their intended audiences.

Third, including intended target audiences throughout the process of developing communication products[156] both promotes procedural justice and increases the likelihood that such efforts meet shared goals.[157,158,159] In parallel, communicators—including formal and informal science educators—may in some cases better meet their own and audiences' goals via setting- and audience-specific trainings that provide a strong grounding in both climate science and effective communication, such as the National Network for Ocean and Climate Change Interpretation.[160,161]

Fourth, efforts that have been successful in engaging people on climate change across existing ideological and cultural divides generally do so by addressing the things people care about most, such as livelihoods, homes, investments, local communities, and family.[154,162,163] It is not always necessary to connect relevant impacts to climate change to motivate action, and doing so can sometimes backfire; for example, providing

environmental-benefit information (green labels) on energy-efficient products decreased the chances of their purchase by conservatives relative to when no label was provided.[164]

Fifth, engagement outcomes also strongly reflect the relationships and levels of trust between intended audiences and messengers. The use of trusted messengers increases acceptance and use of climate change risk information. For example, parents, teachers, peers, and scientists are considered trusted messengers for youth audiences, and the use of targeted messages and trusted messengers can increase engagement even among adversarial audiences;[165,166] similarly, experimental research has found that classroom-based climate change curricula offered to school-aged children can influence the climate change beliefs and engagement of adults who interact with those children.[167]

Sixth, pervasive uncertainty surrounding climate change (including public uncertainty) continues to be a major challenge to communication, but there is evidence that certain practices can help people understand the likelihood and magnitude of expected or possible changes and their implications for decision-making.[168] For science communicators, these include avoiding unfamiliar probabilistic statements and combining verbal and numerical assessments of likelihood—for example, when describing an outcome as "unlikely," simultaneously providing the corresponding numerical assessment of "0%–33%" probability;[169] using visualizations to show probabilistic information;[170] transparently discussing possible ranges for future outcomes or impacts, including both worst- and best-case scenarios;[171] and focusing attention on the types and magnitude of expected impacts rather than on when, specifically, those impacts might occur.[163] Commonly used technical phrases such as "1-in-1,000-year event" can often lead to mistaken beliefs or expectations about the probability of repeat occurrences of disasters such as flooding or wildfire.

## *Implications of Engagement Efforts for Decision-Making and Justice*

A growing evidence base identifies how and when engagement and communication can lead to changes in climate decision-making.[114,172,173,174] Some work suggests that such efforts can, over time, move people from unawareness of the issue to initial awareness to more active and involved engagement at the personal and collective levels.[175] Although many engagement efforts aim to increase knowledge about climate change and climate science or shift attitudes, some efforts are more directly aimed at supporting mitigative and/or adaptive behavior change related to climate change. For example, extensive work on social norms messaging—which communicates information about the behavior of others, or expectations of behavior, and provides cues and social pressure—finds evidence that such information can influence several climate change-relevant behaviors, including household energy consumption.[176]

Efforts to engage diverse groups and communities with the issue of climate change also have critical upstream and downstream justice-related implications. For example, engagement activities or processes that actively work to include diverse stakeholders throughout the knowledge creation and/or application process (in, for example, setting objectives, developing content, and drawing implications) are more procedurally just than top-down efforts that simply attempt to provide actionable information to those groups.[177] Recognitional justice is similarly promoted by inclusive engagement efforts and inhibited when diverse, climate-impacted communities or groups are excluded from the process of setting engagement and/or knowledge-creation objectives. Thus, efforts to engage diverse publics, and the epistemologies and struggles they inhabit, within climate change decision-making are a key mechanism through which justice-related outcomes or objectives can be either realized or thwarted, intentionally or unintentionally.

## Key Message 20.3

## Climate Justice Is Possible If Processes like Migration and Energy Transitions Are Equitable

Climate justice—the recognition of diverse values and past harms, equitable distribution of benefits and risks, and the procedural inclusion of affected communities in decision-making processes—is possible (*medium confidence*). Complex social processes such as human migration affect climate inequities (*medium confidence*). Climate justice is also closely related to just transitions (*high confidence*), which involve equitably adapting societies, economies, and energy systems to climate change mitigation strategies and climate impacts (*high confidence*).

### *Human Migration May Be a Pathway to Climate Justice or Injustice*

The concept of climate justice is useful in understanding how the impacts of climate change, and the impacts of climate change mitigation and adaptation, are distributed across communities. Climate justice recognizes that the inequitable distribution of resources and other social and political capital impacts the capacity for adaptation during times of upheaval, including the upheaval created by climate change. Human migration is a complex response to pressures created by social, political, economic, and environmental systems, including climate change.[178,179] The dynamic interactions among climatic changes, market processes, governance decisions, and historical inequity make human migration a critical example of how climate change interacts with preexisting social processes to alleviate or exacerbate inequity (Figure 20.5).

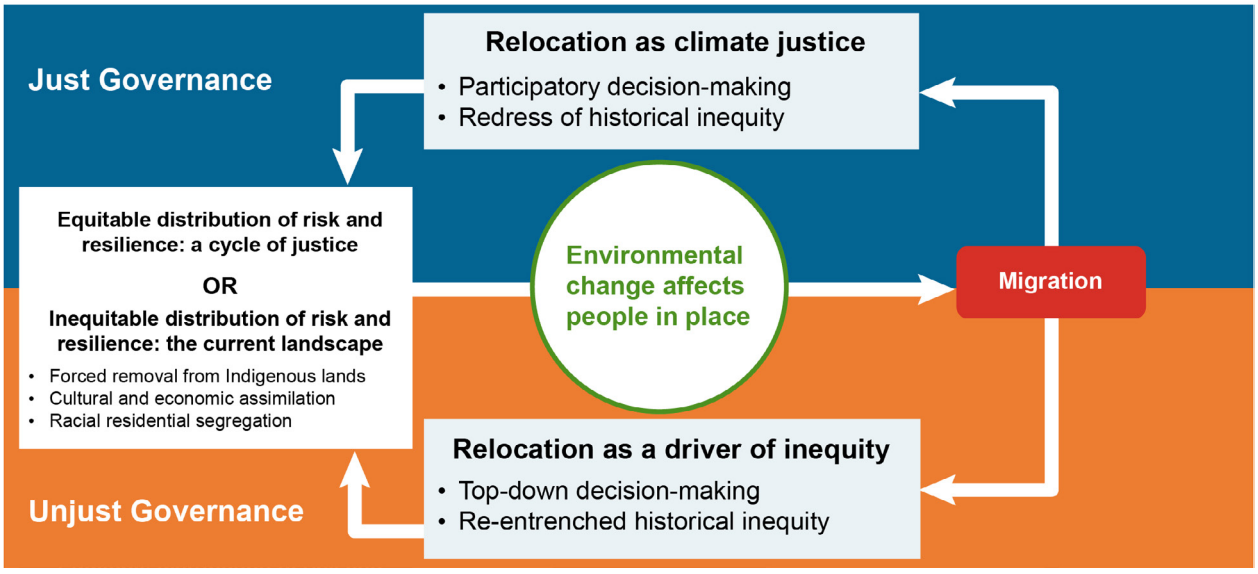
In the United States, climate change–related disasters are not yet a major driver of migration.[180,181] Most counties affected by hurricanes deviate only temporarily from their pre-disaster growth trend, although the demographic composition of affected areas may change.[182,183,184,185] Historically, most communities have adapted to climate hazards by engineering protections and adaptive technologies.[186,187,188] As climate change impacts overwhelm the protective ability of these solutions, as is expected to occur in the future (KM 9.2), communities are expected to adapt by accommodating hazards or by relocating away from hazardous areas.[189,190]

Recent hurricane events illustrate how extreme weather has displaced unprecedented numbers of people, mostly temporarily, and caused billions of dollars in damages.[191,192,193,194,195,196,197,198,199] Tropical storms pose an ongoing threat to about one-fifth of the US population that lives in coastal communities along the Atlantic and Gulf Coasts.[200] Further, every US region experiences climate-related hazards (KMs 21.1, 22.4, 23.3, 24.2, 25.1, 26.1, 27.4, 28.1, 29.2, 30.3). Efforts to predict future migration depend on assumptions about how climate hazards will affect the habitability of places far into the future, mostly informed by models of sea level rise or heat extremes.[201,202] These climate impacts are predicted to unfold gradually and unevenly, producing unpredictable impacts at small temporal and spatial scales. Governance that does or does not anticipate climate hazard events, and does or does not account for past harms, will determine whether migration will exacerbate inequities or offer a pathway toward climate justice (Figure 20.5).

Past experience with weather-related disasters illustrates the complexity of the relationship between environmental change and migration (Figure 20.5). Disasters that destroy housing and infrastructure have the potential to displace people from their homes, neighborhoods, and communities. Yet social systems that govern land and property—such as housing markets, homeowners' insurance, and federal disaster recovery housing assistance—promote in situ housing recovery for most homeowners (but notably not for renters and those with precarious title to property).[203] For example, federal disaster assistance and

private insurance incentivize many homeowners to rebuild in place, a social system that aligns with residents' place attachment.[204,205,206] Homeowners maintain and rebuild their housing to protect its market value and increase its resilience to future hazards.[207] In contrast, historic and ongoing discriminatory real estate practices, such as redlining and predatory lending, sort low-income and BIPOC households into environmentally risky neighborhoods and deteriorated housing[66,208,209] and into rental housing or housing types that are more susceptible to disaster-related damage, such as multiunit buildings and mobile homes.[210,211,212,213,214] The low property values in these neighborhoods and renters' tenuous connection to their homes also make residential mobility after a disaster more likely. For example, homeowners may be unable to repair and rebuild their homes because insurance and disaster recovery assistance align payments with pre-disaster property values, creating large gaps in the ratio of funds to rebuilding costs.[215,216] Rental properties, which house a disproportionate number of low-income and BIPOC households, are rebuilt more slowly than owner-occupied housing, driving up rents and limiting the number of affordable rental units.[203,207,217] Consequently, more residential mobility is observed among renters and those lacking clear title to their property.[182,185,218,219,220] Additionally, upheaval in housing markets after disasters is associated with increases in evictions and gentrification, as real estate speculators buy up deeply discounted properties for development.[221,222,223] Thus, there are multiple housing-related pathways through which low-income and BIPOC households are displaced or compelled to migrate as a result of climate-related disasters. These processes can therefore exacerbate pre-disaster inequalities through unjust governance and unequal distribution of risk and resilience.

## Migration and Governance




**Social systems create just or unjust conditions that influence migration outcomes.**

**Figure 20.5.** Research shows that social systems exert influence on migration. Historically, forced migration has exacerbated inequities and caused social harm. It is not yet understood how these dynamics will play out under conditions of climate change and whether climate-inflected migration can be a pathway toward climate justice. This figure captures, conceptually, how migration may exacerbate inequity or be a remedy. Figure credit: Oregon State University–Cascades, Brown University, Jacksonville State University, and Puget Sound Partnership.

Current US policies governing relocation away from locations where repeated hazard events have occurred involve home buyout programs. Voluntary homeowner buyout programs have been used as a piecemeal strategy for hazard mitigation, often as part of post-disaster recovery assistance.[224,225,226] However, buyout programs often lack transparency, resulting in public distrust and low participation, as well as

disproportionate participation in low-income and BIPOC communities.[227,228] Buyout programs tend to be pursued in counties with higher property values, more home equity, and higher proportions of White residents, yet within these counties a greater number of buyouts tend to occur in BIPOC neighborhoods, suggesting home buyouts are an inequitable mechanism for moving people out of harm's way (KMs 18.2, 21.3, 22.1).[229] Furthermore, home buyout programs have been deemed inadequate to the scale and complexity of managing relocation away from climate-related hazards.[230] Programs designed to relocate residents out of areas exposed to hazards in a way that promotes climate justice would consider these historical and ongoing social inequities and take steps to mitigate their impact.

Relocation as an outcome of flooding can be prevented or forestalled with the preservation and installation of green infrastructure, such as riparian zones, wetlands, trees, parks, and other green stormwater management systems.[231,232,233,234,235] However, if justice is not taken into consideration, these same adaptation projects that alleviate climate-related displacement can cause the displacement of low-income residents, as property values often rise when improvement and hazard mitigation projects are planned and executed, leading long-time residents to be priced out of the market.[236] Climate adaptations therefore can create social risks similar to those of climate-related disasters.

## *What Are Just Transitions?*

Central to climate justice is the concept of a just transition—or just transitions, as approaches may be diverse and locally specific. The idea of a just transition emerged from labor environmentalism in the 1970s. Labor union leaders recognized the need to support workers who lost their jobs due to stricter environmental policies or whose jobs exposed them to toxic materials.[237] Just transition approaches focused on the creation of green jobs and training workers to fill these jobs. In the past 40 years, the concept of just transitions has broadened and now refers to mitigating and adapting to climate change in a managed process that ensures equitable access to jobs, environmental goods, and quality of life.[238] If efforts are made to shift the economy away from fossil fuel extraction, thus displacing workers in coal, oil, gas, and other energy sectors, job creation and training will continue to be vital components of just transitions. This broader approach to just transitions emphasizes that poor and BIPOC communities that have experienced the brunt of environmental injustices, including both pollution and climate change impacts, are the least responsible for these impacts.[239] Without just transitions, these inequities are expected to be exacerbated as society moves away from fossil fuel extraction, responds to climate adaptation and mitigation processes, and shifts toward a sustainable and green society (KMs 5.3, 14.3).[88,240]

Just transitions recognize the capacity of green infrastructure not only to mitigate hazards, capture carbon, and provide local cooling but also to redress past harms and minimize social inequities. For example, decisions about where to place green infrastructure might take into account legacies of unjust social systems and ongoing social inequality that shape the unequal access of BIPOC and low-income communities to environmental amenities and their overexposure to environmental harms.[241,242,243,244]

The green infrastructure equity index can help provide a more nuanced examination of communities and their access to green space.[245] Not taking into account these forms of justice has been shown to contribute to the uneven distribution of urban green infrastructure.[246] Other examples have shown that using spatial tools and indices examining the built environment that include racial, social, and economic indicators can help us understand the inventory, condition, and distribution of green infrastructure[247] and use that information to promote equity.

## *Current Policy Creation as Part of Climate Justice*

Mitigation and adaptation policies and programs are being implemented at federal, state, and municipal scales in multiple sectors (KMs 31.1, 32.5) and have implications for climate justice (KMs 31.2, 32.4). Both Colorado and California have charged agencies with creating plans to guide their transition away from coal, with a focus on economic diversification, job creation, and workforce training for former coal workers. Colorado's Just Transition Action Plan, approved in 2020, acknowledges a commitment to communities disproportionately impacted by coal power pollution.[248] California's Office of Planning and Research is in the process of creating a Just Transition Roadmap. Executive Order N-79-20, which mandates the roadmap's creation, includes language highlighting the disproportionate impact of coal pollution on low-income and BIPOC communities; however, it is still uncertain whether the roadmap, like Colorado's plan, will be focused on former coal workers.[249]

The Federal Government has also enacted a portfolio of environmental, climate, and economic justice policies that seek to ensure no one is left behind by climate change and energy transformations. These are examples of policies that seek to incorporate climate justice into governance structures. The Justice40 Initiative,[250] a policy that aims to ensure that 40% of the benefits in these investments flow directly to disadvantaged communities, is one example. Other indices and geospatial and measurement tools—such as the Climate and Economic Justice Screening Tool and the National Risk Index—have been developed to gauge whether climate exposures and impacts or the impacts of climate adaptation and mitigation are being distributed equitably. In addition, federal civil rights laws such as Title VI of the Civil Rights Act of 1964,[251] Section 504 of the Rehabilitation Act of 1973,[252] and Section 308 of the Stafford Act[253] are written to ensure that the implementation of environmental, climate, and economic policies do not discriminate against protected classes. The outcomes of these programs and the efficacy of these indices in leading to just and equitable access to resources have yet to be realized or analyzed.

## Box 20.1. Quinault Indian Nation Relocation and Sovereignty

The Quinault Indian Reservation, located along the central coast of Washington State, is experiencing an accelerated loss of land caused by sea level rise, flooding, and erosion. To adapt, the Quinault Indian Nation (QIN) is relocating the Quinault Tribal community from their traditional village site, where they have lived and to which they have been tied since time immemorial, to a newly developed site at higher elevation.

Meaningful community engagement throughout relocation decision-making processes facilitates participation that recognizes community values and culture. Community engagement means engagement that involves local experts and nonexperts and allows impacted populations to have decision-making power and consent pathways (KM 16.3). This kind of engagement can be a profound way to incorporate local wisdom and values. Reflecting on possibly relocating, a Quinault Tribal member shared this sentiment: "I've made my life living off of the land and the water, and if it's my turn to give something back, I'll go with it" (interview with community member quoted in Watkinson-Schutten 2022[254]).

While many Indigenous communities are concerned with carrying out plans that consider seven generations into the future, historic US policies imposed on American Indian Tribes and other Indigenous communities have greatly limited Tribal self-determination to conduct long-term planning that allows the Tribe to adapt to changing conditions. Land allotment and assimilation policies that led to the fractionation of lands, for example, impact the available relocation sites that would help QIN adapt to climate change. Reacquiring and consolidating Tribal trust land through buyback programs enhances the adaptive capacity of Tribes experiencing climate change impacts.[254]

### Relocation and Tribal Sovereignty

**Quinault Indian Nation engaged the full community in its village relocation plan.**

**Figure 20.6.** Community members gather for a ribbon cutting for Quinault Indian Nation's New Generations Building in Taholah, Washington. In March 2014, the Quinault Indian Reservation hired planners to work with the community to develop a plan for the relocation of the village. The master plan resulting from this effort directs the development of a new village beyond the tsunami zone and flooding inundation areas. The new village will replicate the uses in the lower village and will include single and multifamily residential, commercial, public, and institutional land uses. The plan also includes new streets and provides for open spaces, parks, and other recreational facilities. Photo credit: ©Larry Workman, Quinault Indian Nation.

# Traceable Accounts

## *Process Description*

This chapter's authors have scientific knowledge and credibility in the topical areas covered. In particular, the authors span a variety of social science disciplines, allowing the team to analyze social systems from multiple disciplinary perspectives. Author selection for the chapter proceeded as follows.

First, the US Global Change Research Program (USGCRP) released a Request for Public Nominations. Interested scientists were either nominated or self-nominated and their names placed into a database. A concurrent Request for Public Nominations also solicited scientists to serve as chapter leads. Both lists were reviewed by the USGCRP, with input from the coordinating lead author (CLA) and from the National Climate Assessment (NCA) Federal Steering Committee. All chapter lead (CL) and agency chapter lead (ACL) authors were selected by the USGCRP. The CLA, CL, and ACLs then convened to review the author nominations list and identify potential chapter authors. The list was coded for diverse disciplinary expertise, and a subset was identified that met our requirements for analysis.

In the second phase, the CLA and CL used both the list of nominees and a list of other scientists who had relevant expertise to build an author team that was representative of diverse social science disciplines, institutional affiliations (federal agencies and academic and research institutions), depth of subject-matter expertise, and knowledge of proposed topics.

Lastly, the authors were contacted by the CL to determine their level of interest and willingness to serve as experts on the first Human Social Systems chapter in the NCA. One author, Dr. Kyle Whyte, was invited to lead a different chapter of the NCA after the process had begun. Because his disciplinary expertise was needed on this chapter, Dr. Whyte was asked to remain as an author on this chapter as well. Although this was unusual, all authors felt it was the best course of action given the team's ongoing conversations.

In January 2022, the author team held a public engagement workshop, where the public was invited to weigh in on the prospectus stage of our chapter. Public comments were therefore incorporated at multiple stages of chapter development.

To ensure Tribal sovereignty, the chapter lead, Elizabeth Marino, chapter author Melissa Watkinson-Schutten, and the NCA5 director, Allison Crimmins, discussed and consulted on the contents of Box 20.1 and accompanying photograph with the Tribal Council of Quinault Indian Nation. Formal permission was received through a vote to include this information in this NCA chapter.

## Key Message 20.1

# Social Systems Are Changing the Climate and Distributing Its Impacts Inequitably

### Description of Evidence Base

Decades of rigorous social science research identifies numerous human-caused drivers of climate change, with the burning of fossil fuels and resulting greenhouse gas (GHG) emissions being of great importance.[11,255,256] Human-caused drivers encompass social systems and individual and aggregated human actions causing GHG emissions, as well as societal factors shaping and conditioning those actions, emphasizing institutional or large-scale processes of social structure. Most research on how social systems produce and distribute climate change focuses on anthropogenic drivers and involves longitudinal analyses of carbon emissions for the world's nations, while subnational analyses of emissions, including for US states and smaller units such as corporations and power plants, are becoming increasingly common (e.g., Galli-Robertson and Collins 2019;[257] Grant et al. 2020;[10] Jorgenson et al. 2019;[61] Pulver and Manski 2021[258]). To generate the body of knowledge summarized here, researchers merge aggregate data for societal factors (e.g., economic growth, population, inequality, etc.) with emissions data and use many statistical modeling techniques, such as multilevel regression analysis and longitudinal regression analysis, to examine changes over time and to test linear and nonlinear hypotheses regarding the relationships between social systems and emissions.[259]

Empirical research seeks to analyze these processes and interrelationships at different spatial scales and temporal resolutions. When the unit of analysis is the nation-state, analyses usually examine data for most of the world's nations or are grouped in categories like higher- and lower-income nations or as particular regional clusters. Economic development (e.g., industrialization, GDP growth, wealth) and population dynamics (e.g., population size, population growth) are the most widely analyzed anthropogenic drivers. Other societal factors with many dimensions are analyzed as well, such as urbanization, which may lead to different findings, depending on which dimension is being modeled (e.g., urban density, urban slum prevalence, percent of overall population residing in urban areas) and at which scale (e.g., cross-national, subnational).[61,255]

Analyses of governance are often found in public policy and political science research. These literatures recognize that governments are frequently in the position to support human well-being and survival through policy interventions but also demonstrate that these policy processes interact with the institutions and conventions of human social systems and can play a role in the perpetuation of structural inequalities.

It is well-documented that land-use policies, including historic practices such as redlining and other governmental decisions, have concentrated hazard risk into zones of vulnerability and largely determined who will inhabit those zones.[260,261,262] Some disaster risk-reduction strategies and policy decisions function as disaster risk creation, while disaster relief has been shown to incentivize poor land-use decisions by local government.[263,264,265] An extensive literature exists in fields such as public administration, social geography, and political science, providing an evidence base that is generally in agreement regarding the role that governance and institutional arrangements play.

### Major Uncertainties and Research Gaps

Although addressing human drivers is necessary for reducing GHG emissions, how to effectively harness global drivers of change is uncertain, given institutional inertia and the complexity of cross-scale social change. Curbing economic growth is not expected to proceed evenly at a global scale, given unbalanced resources, policies, and institutional mechanisms to promote change. The scale at which mitigation of

human drivers can be most effective is unclear, as efforts need to be multi-scalar and operate across various social-structural and spatial contexts.

There is uncertainty as to whether bureaucratic discretion can be utilized in service of adaptive governance, as opposed to when legal and regulatory changes are needed. Scholars are investigating the bounds of law and policy that limit and create options for climate adaptation, risk reduction, and support for communities faced with structural racism and discrimination. Transformative adaptive governance is only possible if there is action at all levels of government and civil society.[266] This action is dependent on key governance choices, including what problems to focus resources on, at what level of government actions should be taken, the timing of such actions, the mode of governance to be utilized, and what norms to rely on.[267] More research would be needed in order to identify the limitations of discretion and how best to build adaptive governance mechanisms.

Another important gap is a lack of alternatives to cost–benefit mechanisms, such as models that can account for the value of preserving community, protecting lifeways, and accounting for historic disenfranchisement that drives down economic value.

## Description of Confidence and Likelihood

There is an extensive body of empirical research in the social sciences on the societal drivers of climate change.[61,255,268] Therefore, there is *very high confidence* that social systems create climate change via GHG emissions and that these emissions are mitigated by societal characteristics. Empirical research and theoretical modeling of human activity show that human systems demonstrably impact the atmospheric conditions of the Earth. A diverse set of studies also show that world economic integration, ongoing economic growth, population growth, and high levels of inequality are correlated with GHG emissions and continue to trend upward. A large body of research demonstrates correlations in world economic integration, life expectancy, and income distribution with GHG emissions. This body of literature is unambiguous. Therefore, the authors have *very high confidence* that social systems also inequitably distribute the benefits of energy consumption and the impacts of GHG emissions.

Case study literature and disaster studies for at least 40 years have shown that disasters do not affect everyone equitably; therefore, authors also have *high confidence* that the impacts of climate will be distributed inequitably. Public administration research, as well as case study literature from geography and anthropology, corroborates this claim.

The interactions between a variety of governance processes and hazards and disasters are well studied. Land-use policies, and in particular their impacts, have been studied in depth and show disparate impacts over time.[265,269] Institutional decisions, policies, and bureaucratic discretion have also been shown to cause greater harm to some populations than to others.[270,271] Here the authors do not suggest that inequitable distribution of climate impacts is certain in the future, but there is a robust literature that suggests governance decisions are clearly linked to how risk emerges within human and social life, thus leading to an assessment of *very high confidence*. There is research that demonstrates adaptive measures to climate changes, such as hazard mitigation, are similarly structured by governance decisions; but because there is a much shorter time frame for studying climate change–specific adaptation, authors have assigned *medium confidence*.

## Key Message 20.2

# Social Systems Structure How People Know and Communicate About Climate Change

### Description of Evidence Base

There is a rapidly increasing, diverse, and transdisciplinary evidence base supporting the conclusion that social systems structure how people understand, think about, and respond to climate change in fundamental ways. Work on this topic comes out of philosophy, science and technological studies, intellectual history, Indigenous studies, psychology, sociology, and anthropology, among other fields, and includes a wide diversity of theoretical and methodological approaches to evidence gathering (including epistemological studies, survey research, ethnography, and others).

The evidence base includes studies that demarcate the diverse ways in which human–nature interactions are conceived, including worldviews that integrate human and nonhuman society. The evidence base also includes research that demonstrates that insights Indigenous Peoples and others make about climate drivers and action reflect their social position, history, culture, and connectedness to the environment.[77,105,119,122,123,125,128,163,272,273,274]

A robust literature in social psychology and science communication, among other fields, demonstrates how people respond to different messages and information about climate change and why different types of climate change engagement efforts have differential outcomes. These fields offer insight into how effective communication and engagement can promote decision-making and action through multiple pathways, including provision of actionable knowledge, growth of motivation to act, and development of new skills and sense of efficacy. However, while there is often much hope around initiatives to change household behaviors through communications and engagement, the impacts of these initiatives are oftentimes relatively small, if generally robust.[172,173]

### Major Uncertainties and Research Gaps

The literature is clear that knowledge is influenced by social position, culture, and history, and that knowledge and justice are related; it is also clear that people engage with climate change in diverse ways as a function of who they are and how efforts to communicate climate change are designed and delivered. There are significant gaps in the relevant research base, however. One is that studies are only beginning to emerge that show how people who experience injustice related to climate change envision different solutions to climate change. While the available evidence is strong in some domains, such as fire management,[109,110] it is not comprehensive in other domains, such as with respect to responses among diverse BIPOC (Black, Indigenous, and People of Color) communities and communities with lower incomes that are experiencing a range of impacts and challenges. In addition, in part because it is so broad and comes from many different fields of study, the evidence base regarding social systems and how people understand and engage with climate change lacks integration across fields (and even within subfields). Although there are growing efforts to use coproduction approaches, as well as meta-analytic and other synthesizing approaches, to study social systems, there is a clear need for additional synergistic and interdisciplinary research that explores these issues from a diverse set of perspectives and using diverse methodological tools. Additionally, there is a need for more studies that employ coproduction approaches to understand more about how diverse knowledge contributes to climate adaptation and mitigation among communities that have been shaped by prior unjust experiences.[138,139,140]

While guidance to improve communications and engagement efforts has grown and strengthened in the past decades, there are also areas of uncertainty and research gaps in this domain. One such area concerns

the role of emotion in engagement and communication. Researchers and practitioners debate whether messages that evoke fear, guilt, hope, or other emotions can motivate behavior change effectively.[275] Climate communication that appeals to different emotions as a means to engage audiences and spur action is a growing research area, but there are conflicting findings about its effectiveness. Another research gap due to a lack of qualitative and quantitative studies involves the communication needs of vulnerable populations.[148] More generally, extant evidence tends to come from correlational studies and relatively small-scale and/or lab-based experiments with nonrepresentative samples, and there are open questions in the literature regarding the robustness, generalizability, and applicability of the research base to real-world engagement and communication efforts.

## Description of Confidence and Likelihood

There is extensive evidence in both case study and other research that people's context impacts their understanding of knowledge and, in turn, how they experience climate change. Therefore, we have *high confidence* that people's histories, educations, cultures, and ethics determine how they understand climate change. Given the cultural diversity of knowledge and knowledge communication found in anthropology and other fields, we have *high confidence* that these knowledges take different forms.

Although there is evidence from within and beyond the climate change domain to suggest that clear objectives and benchmarks promote desired outcomes regarding public engagement efforts, there are gaps with regard to the diversity of communities that have been formally studied. For example, much attention has been dedicated to communicating more effectively across ideological divides. On the other hand, the authors identify research gaps regarding knowledge of the communication needs of overburdened communities that are potentially most vulnerable to climate change impacts. Therefore, the authors have *medium confidence* that building such components into engagement efforts will actually promote desired outcomes across diverse communities.

There is extensive evidence across multiple fields of study and practice that converges on a consistent finding: namely, that climate change is a challenging issue on which to engage diverse publics. This is due in part to the complex nature of the issue, as well as to pervasive deep uncertainty, such as tipping points, within the climate system and how social systems (including political systems and governance) will continue to adapt to evolving risks. Therefore, the author team has *high confidence* that these and other factors pose significant challenges to effective engagement.

Although there is a growing recognition of the importance of community-driven engagement and inclusion of diverse forms of knowledge in collective decision-making in the climate change space, relatively less attention has been paid in the literature to promoting (climate) justice through inclusion of diverse perspectives and epistemologies. Therefore, the existing evidence base provides for *medium confidence* that greater inclusion of diverse community perspectives and types of knowing in engagement and decision-making efforts can provide an effective mechanism to promote justice.

## Key Message 20.3

## Climate Justice Is Possible If Processes Like Migration and Energy Transitions Are Equitable

### Description of Evidence Base

Research on environmental migration and relocation is represented in multiple social science disciplines, including demography, sociology, geography, anthropology, regional and urban planning, and urban studies. Research methods vary widely, from ethnography and other qualitative approaches to statistical analysis of survey, census, and administrative records and to scenario-based modeling. Much of the empirical research focuses on migration in response to extreme disaster events in order to speculate on future climate–migration interactions. Therefore, event-based case study approaches dominate the literature.[276,277] Meta-analyses of the climate migration literature have shown that hazards have heterogeneous effects on human migration, sometimes driving people out of and sometimes attracting people to hazard-affected areas and sometimes not having any effect.[278,279,280,281,282] In the United States, a few surveys ask respondents why they moved, although only very small percentages (less than 1%) name disasters or the environment as their reason for moving,[180,181] supporting the statement that the environment is not a major driver of internal US migration. Research on governance of housing recovery after disasters is based on a growing body of evidence about disaster impacts on housing, post-disaster permanent housing recovery, home buyout programs, and social and spatial inequalities therein, which originated in disaster research centers and has expanded to include scholars in all of the aforementioned disciplines.

This Key Message and supporting text were based on the extensive environmental justice, climate justice, and just transition literature. The overburdening and overexposure of low-income and BIPOC communities to environmental injustices and negative climate change impacts, as well as their lack of access to environmental amenities and green spaces, has been well documented, particularly by scholars such as Robert Bullard (e.g. Bullard 1994,[1] 1996,[241] 2001,[242] 2008[74]).

While the majority of environmental justice literature focuses on the distributional arm of justice, some key literature has discussed and demonstrated the importance of recognitional and procedural justice ameliorating histories of environmental injustices (e.g., Corburn 2003;[283] Rigolon and Németh 2018;[284] Whyte 2011[3]). The literature on just transition largely focuses on the transition to a low-carbon economy via the increased use of green energy.[238] Much of that literature is based on European case studies. As such, there are not many US case studies to discuss, and even fewer successful ones. However, the literature on green infrastructure, which can be considered a part of just transition strategies, is better developed, although it is still evolving (e.g., Zuniga-Teran et al. 2021[246]). Nevertheless, the literature available on these topics, albeit limited in some areas, is corroborating, clear, consistent, and overwhelmingly in agreement regarding the history of environmental racism, the evidence of disparate exposure and impact, and the potential for perpetuation in the context of climate.

### Major Uncertainties and Research Gaps

There are several research gaps within this research areas. One such area is research on nontraditional hazardous scenarios or built-environment challenges, including the distribution and condition of critical infrastructure systems and utility services that pose risks in the instance of failure.[247] One well-known example of this is the Flint, Michigan, water crisis and the disrepair of drinking water systems that resulted in corrosion and lead poisoning in a majority-Black community. Emerging literatures are filling this gap in terms of justice in the areas of energy, sewerage, stormwater, transport infrastructure, and beyond. Similarly, research in just transitions is still developing, especially with regard to green energy and jobs, two

of the major focuses of the literature, and has few resolved or successful case studies. This is mainly because this phenomenon is relatively recent and the outcomes related to efforts are still to be determined.

Observational studies of environmental drivers of migration cannot predict the quantity or types of migration that will occur in the future, especially as changes occur in the environment, the economy, governance, risk perception, and systems exacerbating or mitigating social inequalities. Scenarios of expected conditions may allow for broad generalizations;[285] however, predicting the timing, location, and magnitude of climate-related hazards that may provoke migration requires many assumptions and uncertainties (e.g., Rigaud et al. 2018;[286] Clement et al. 2021[287]). Social science may contribute to filling a gap regarding how social systems influence collective and individual decisions to relocate away from or adapt in place to climate change impacts. There are growing literatures on immobility, whether climate induced[288] or voluntary.[289] Additional research gaps enumerated in a recent review include investigations of the long-term outcomes of disaster evacuees and the effects of climate change on demographic subgroups, such as children or older adults, and small populations, such as Indigenous People.[290]

There are not enough data available to evaluate the new federal initiatives mentioned in this section. In the past it has been challenging to understand environmental justice implications in federal policies because of a lack of data. FEMA, for example, has not historically collected data on race or ethnicity as part of its assistance programs. Recent changes have permitted this data to be collected,[291] and we anticipate new insights in the coming years.

## Description of Confidence and Likelihood

Historical corollaries and new policies on environmental justice provide an opportunity for communities to envision climate justice; however, current case study research and ongoing research on environmental justice outcomes show that such a transition will be difficult and that there remain deep inequities in accessing environmental benefits and suffering environmental burdens. Additionally, it is unclear whether governance structures can adapt quickly enough to respond to climate risks and other societal pressures. There is therefore *medium confidence* that climate justice is possible. An extensive literature in demography, anthropology, geography, public administration, and legal studies demonstrates that migration is a complex phenomenon that has multiple push and pull factors and is mitigated by socioeconomic conditions. This research base gives us *medium confidence* that migration will impact the three categories of environmental justice or exacerbate these injustices. There is extensive literature that suggests justice is a complex, multifaceted process that includes understanding how benefits, burdens, and decision-making around climate change are distributed among diverse groups;[1] therefore, we have *high confidence* that adaptation to a changing climate and changes to energy production require a whole-systems approach that must consider the social dynamics of race, ethnicity, rurality, poverty, and infrastructure equity, among other factors.

# References


1. Bullard, R.D., Ed. 1994: *Unequal Protection: Environmental Justice and Communities of Color*. Sierra Club Books, San Francisco, CA, 400 pp. https://doi.org/10.1177/027046769501500454

2. Foster, S.R., 1998: Justice from the ground up: Distributive inequities, grassroots resistance, and the transformative politics of the environmental justice movement. *California Law Review*, **86**, 775. https://ir.lawnet.fordham.edu/faculty_scholarship/295

3. Whyte, K.P., 2011: The recognition dimensions of environmental justice in Indian Country. *Environmental Justice*, **4** (4), 199–205. https://doi.org/10.1089/env.2011.0036

4. Yakubu, O.H., 2018: Delivering environmental justice through environmental impact assessment in the United States: The challenge of public participation. *Challenges*, **9** (1), 9. https://doi.org/10.3390/challe9010009

5. Dietz, T., R.L. Shwom, and C.T. Whitley, 2020: Climate change and society. *Annual Review of Sociology*, **46** (1), 135–158. https://doi.org/10.1146/annurev-soc-121919-054614

6. Fisher, D.R., L. Jasny, J. Redmond, and F. Heaume, 2021: Ch. 16. Environmental governance. In: *Handbook of Environmental Sociology*. Caniglia, B., A. Jorgenson, S. Malin, L. Peek, D. Pellow, and X. Huang, Eds. Springer, Cham, Switzerland, 333–353. https://doi.org/10.1007/978-3-030-77712-8_16

7. Klinenberg, E., M. Araos, and L. Koslov, 2020: Sociology and the climate crisis. *Annual Review of Sociology*, **46** (1), 649–669. https://doi.org/10.1146/annurev-soc-121919-054750

8. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

9. Dunlap, R.E. and R.J. Brulle, Eds., 2015: *Climate Change and Society: Sociological Perspectives*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199356102.001.0001

10. Grant, D.O.N., A. Jorgenson, and W. Longhofer, 2020: *Super Polluters: Tackling the World's Largest Sites of Climate-Disrupting Emissions*. Columbia University Press. http://www.jstor.org/stable/10.7312/gran19216

11. IPCC, 2022: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926

12. Longo, S.B., E. Isgren, B. Clark, A.K. Jorgenson, A. Jerneck, L. Olsson, O.M. Kelly, D. Harnesk, and R. York, 2021: Sociology for sustainability science. *Discover Sustainability*, **2** (1), 47. https://doi.org/10.1007/s43621-021-00056-5

13. Bruckner, B., Y. Shan, C. Prell, Y. Zhou, H. Zhong, K. Feng, and K. Hubacek, 2023: Ecologically unequal exchanges driven by EU consumption. *Nature Sustainability*, **6**, 587–598. https://doi.org/10.1038/s41893-022-01055-8

14. Givens, J., X. Huang, and A. Jorgenson, 2019: Ecologically unequal exchange: A theory of global environmental injustice. *Sociology Compass*, **13** (5), 12693. https://doi.org/10.1111/soc4.12693

15. Huang, X., 2018: Ecologically unequal exchange, recessions, and climate change: A longitudinal study. *Social Science Research*, **73**, 1–12. https://doi.org/10.1016/j.ssresearch.2018.03.003

16. Prell, C. and L. Sun, 2015: Unequal carbon exchanges: Understanding pollution embodied in global trade. *Environmental Sociology*, **1** (4), 256–267. https://doi.org/10.1080/23251042.2015.1114208

17. Roberts, J.T. and B. Parks, 2006: A *Climate of Injustice: Global Inequality, North-South Politics, and Climate Policy*. MIT Press, Cambridge, MA, 424 pp. https://mitpress.mit.edu/9780262681612/a-climate-of-injustice/

18. Greiner, P.T., 2022: Colonial contexts and the feasibility of mitigation through transition: A study of the impact of historical processes on the emissions dynamics of nation-states. *Global Environmental Change*, **77**, 102609. https://doi.org/10.1016/j.gloenvcha.2022.102609

19. Thombs, R. and X. Huang, 2019: Uneven decoupling: The economic growth–$CO_2$ emissions relationship in the global north, 1870 to 2014. *Sociology of Development*, **5** (4), 410–427. https://doi.org/10.1525/sod.2019.5.4.410

20. Wood, R., M. Grubb, A. Anger-Kraavi, H. Pollitt, B. Rizzo, E. Alexandri, K. Stadler, D. Moran, E. Hertwich, and A. Tukker, 2020: Beyond peak emission transfers: Historical impacts of globalization and future impacts of climate policies on international emission transfers. *Climate Policy*, **20** (sup1), S14–S27. https://doi.org/10.1080/14693062.2019.1619507

21. Briscoe, M.D., J.E. Givens, and M. Alder, 2021: Intersectional indicators: A race and sex-specific analysis of the carbon intensity of well-being in the United States, 1998–2009. *Social Indicators Research*, **155** (1), 97–116. https://doi.org/10.1007/s11205-021-02613-x

22. Givens, J.E., O.M. Kelly, A.K. Jorgenson, M.A. Long, M.J. Lynch, and P.B. Stretesky, 2023: Ch. 18. Inequality, emissions, and human well-being. In: *Handbook of Inequality and the Environment*. Long, M.A., M.J. Lynch, and P.B. Stretesky, Eds. Edward Elgar Publishing, 305–321. https://www.e-elgar.com/shop/gbp/handbook-on-inequality-and-the-environment-9781800881129.html

23. Podobnik, B., 2006: *Global Energy Shifts: Fostering Sustainability in a Turbulent Age*. Temple University Press, Philadelphia, PA, 240 pp. http://www.jstor.org/stable/j.ctt14bs7mx

24. Thombs, R.P., 2022: The asymmetric effects of fossil fuel dependency on the carbon intensity of well-being: A U.S. state-level analysis, 1999–2017. *Global Environmental Change*, **77**, 102605. https://doi.org/10.1016/j.gloenvcha.2022.102605

25. Dietz, T., E.A. Rosa, and R. York, 2012: Environmentally efficient well-being: Is there a Kuznets curve? *Applied Geography*, **32** (1), 21–28. https://doi.org/10.1016/j.apgeog.2010.10.011

26. Givens, J.E., 2018: Ecologically unequal exchange and the carbon intensity of well-being, 1990–2011. *Environmental Sociology*, **4** (3), 311–324. https://doi.org/10.1080/23251042.2018.1436878

27. Jorgenson, A.K., 2014: Economic development and the carbon intensity of human well-being. *Nature Climate Change*, **4** (3), 186–189. https://doi.org/10.1038/nclimate2110

28. Kelly, O., 2020: The silver bullet? Assessing the role of education for sustainability. *Social Forces*, **99** (1), 178–204. https://doi.org/10.1093/sf/soz144

29. Knight, K.W. and E.A. Rosa, 2011: The environmental efficiency of well-being: A cross-national analysis. *Social Science Research*, **40** (3), 931–949. https://doi.org/10.1016/j.ssresearch.2010.11.002

30. Lamb, W.F. and J.K. Steinberger, 2017: Human well-being and climate change mitigation. *WIREs Climate Change*, **8** (6), e485. https://doi.org/10.1002/wcc.485

31. Mazur, A. and E. Rosa, 1974: Energy and life-style. *Science*, **186** (4164), 607–610. http://www.jstor.org/stable/1739169

32. Roberts, J.T., J.K. Steinberger, T. Dietz, W.F. Lamb, R. York, A.K. Jorgenson, J.E. Givens, P. Baer, and J.B. Schor, 2020: Four agendas for research and policy on emissions mitigation and well-being. *Global Sustainability*, **3**, e3. https://doi.org/10.1017/sus.2019.25

33. Steinberger, J.K. and J.T. Roberts, 2010: From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975–2005. *Ecological Economics*, **70** (2), 425–433. https://doi.org/10.1016/j.ecolecon.2010.09.014

34. Burke, P.J., M. Shahiduzzaman, and D.I. Stern, 2015: Carbon dioxide emissions in the short run: The rate and sources of economic growth matter. *Global Environmental Change*, **33**, 109–121. https://doi.org/10.1016/j.gloenvcha.2015.04.012

35. Dietz, T. and E. Rosa, 1997: Effects of population and affluence on $CO_2$ emissions. *Proceedings of the National Academy of Sciences of the United States of America*, **94** (1), 175–179. https://doi.org/10.1073/pnas.94.1.175

36. Feng, K., S.J. Davis, L. Sun, and K. Hubacek, 2015: Drivers of the US $CO_2$ emissions 1997–2013. *Nature Communications*, **6** (1), 7714. https://doi.org/10.1038/ncomms8714

37. Haberl, H., D. Wiedenhofer, D. Virág, G. Kalt, B. Plank, P. Brockway, T. Fishman, D. Hausknost, F. Krausmann, B. Leon-Gruchalski, A. Mayer, M. Pichler, A. Schaffartzik, T. Sousa, J. Streeck, and F. Creutzig, 2020: A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, Part II: Synthesizing the insights. *Environmental Research Letters*, **15** (6), 065003. https://doi.org/10.1088/1748-9326/ab842a

38. Jorgenson, A.K. and B. Clark, 2012: Are the economy and the environment decoupling? A comparative international study, 1960–2005. *American Journal of Sociology*, **118** (1), 1–44. https://doi.org/10.1086/665990

39. Rosa, E.A., R. York, and T. Dietz, 2004: Tracking the anthropogenic drivers of ecological impacts. *Ambio*, **33** (8), 509–512. https://doi.org/10.1579/0044-7447-33.8.509

40. Thombs, R., 2018: The transnational tilt of the treadmill and the role of trade openness on carbon emissions: A comparative international study, 1965–2010. *Sociological Forum*, **33** (2), 422–442. https://doi.org/10.1111/socf.12415

41. York, R., 2012: Asymmetric effects of economic growth and decline on $CO_2$ emissions. *Nature Climate Change*, **2**, 762–764. https://doi.org/10.1038/nclimate1699

42. Adua, L., 2022: Super polluters and carbon emissions: Spotlighting how higher-income and wealthier households disproportionately despoil our atmospheric Commons. *Energy Policy*, **162**, 112768. https://doi.org/10.1016/j.enpol.2021.112768

43. Jorgenson, A., J. Schor, and X. Huang, 2017: Income inequality and carbon emissions in the United States: A state-level analysis, 1997–2012. *Ecological Economics*, **134**, 40–48. https://doi.org/10.1016/j.ecolecon.2016.12.016

44. Knight, K., J. Schor, and A. Jorgenson, 2017: Wealth inequality and carbon emissions in high-income countries. *Social Currents*, **4** (5), 403–412. https://doi.org/10.1177/2329496517704872

45. McGee, J.A. and P.T. Greiner, 2018: Can reducing income inequality decouple economic growth from $CO_2$ emissions? *Socius*, **4**, 2378023118772716. https://doi.org/10.1177/2378023118772716

46. Vesia, D.J., M.C. Mahutga, and B.K.H. Buì, 2021: Flattening the curve? The structure of the natural resource exchange network and $CO_2$ emissions. *Social Networks*, **75**, 118–136. https://doi.org/10.1016/j.socnet.2021.07.004

47. Hubacek, K., G. Baiocchi, K. Feng, R.M. Castillo, L. Sun, and J. Xue, 2017: Global carbon inequality. *Energy, Ecology and Environment*, **2**, 361–369. https://doi.org/10.1007/s40974-017-0072-9

48. Bradford, J.H. and A.M. Stoner, 2017: The treadmill of destruction in comparative perspective: A panel study of military spending and carbon emissions, 1960–2014. *Journal of World-Systems Research*, **23** (2), 298–325. https://doi.org/10.5195/jwsr.2017.688

49. Clark, B., A. Jorgenson, and J. Kentor, 2010: Militarization and energy consumption: A test of treadmill of destruction theory in comparative perspective. *International Journal of Sociology*, **40** (2), 23–43. https://doi.org/10.2753/ijs0020-7659400202

50. Smith, C. and M. Lengefeld, 2020: The environmental consequences of asymmetric war: A panel study of militarism and carbon emissions, 2000–2010. *Armed Forces & Society*, **46** (2), 214–237. https://doi.org/10.1177/0095327x19832615

51. Jorgenson, A.K., B. Clark, and J. Kentor, 2010: Militarization and the environment: A panel study of carbon dioxide emissions and the ecological footprints of Nations, 1970–2000. *Global Environmental Politics*, **10** (1), 7–29. https://doi.org/10.1162/glep.2010.10.1.7

52. Belcher, O., B. Neimark, and P. Bigger, 2020: The U.S. military is not sustainable. *Science*, **367** (6481), 989–990. https://doi.org/10.1126/science.abb1173

53. Crawford, N.C., 2022: *The Pentagon, Climate Change, and War: Charting the Rise and Fall of U.S. Military Emissions*. The MIT Press, 392 pp. https://mitpress.mit.edu/9780262047487/the-pentagon-climate-change-and-war/

54. Jorgenson, A.K., B. Clark, R.P. Thombs, J. Kentor, J.E. Givens, X. Huang, H.E. Tinay, D. Auerbach, and M.C. Mahutga, 2023: Guns versus climate: How militarization amplifies the effect of economic growth on carbon emissions. *American Sociological Review*, **88** (3), 418–453. https://doi.org/10.1177/00031224231169790

55. Hironaka, A., 2014: *Greening the Globe: World Society and Environmental Change*. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/cbo9781139381833

56. Longhofer, W. and A. Jorgenson, 2017: Decoupling reconsidered: Does world society integration influence the relationship between the environment and economic development? *Social Science Research*, **65**, 17–29. https://doi.org/10.1016/j.ssresearch.2017.02.002

57. McGee, J., P. Greiner, M. Christensen, C. Ergas, and M. Clement, 2020: Gender inequality, reproductive justice, and decoupling economic growth and emissions: A panel analysis of the moderating association of gender equality on the relationship between economic growth and $CO_2$ emissions. *Environmental Sociology*, **6** (3), 254–267. https://doi.org/10.1080/23251042.2020.1736364

58. Liddle, B., 2013: Population, affluence, and environmental impact across development: Evidence from panel cointegration modeling. *Environmental Modelling & Software*, **40**, 255–266. https://doi.org/10.1016/j.envsoft.2012.10.002

59. Lohwasser, J., A. Schaffer, and A. Brieden, 2020: The role of demographic and economic drivers on the environment in traditional and standardized STIRPAT analysis. *Ecological Economics*, **178**, 106811. https://doi.org/10.1016/j.ecolecon.2020.106811

60. York, R., E. Rosa, and T. Dietz, 2003: STIRPAT, IPAT and ImPACT: Analytic tools for unpacking the driving forces of environmental impacts. *Ecological Economics*, **46** (3), 351–365. https://doi.org/10.1016/s0921-8009(03)00188-5

61. Jorgenson, A., S. Fiske, K. Hubacek, J. Li, T. McGovern, T. Rick, J. Schor, W. Solecki, R. York, and A. Zycherman, 2019: Social science perspectives on drivers of and responses to global climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **10** (1), 554. https://doi.org/10.1002/wcc.554

62. Hubacek, K., G. Baiocchi, K. Feng, and A. Patwardhan, 2017: Poverty eradication in a carbon constrained world. *Nature Communications*, **8** (1), 912. https://doi.org/10.1038/s41467-017-00919-4

63. Grant, D. and I.B. Vasi, 2017: Civil society in an age of environmental accountability: How local environmental nongovernmental organizations reduce U.S. power plants' carbon dioxide emissions. *Sociological Forum*, **32** (1), 94–115. https://doi.org/10.1111/socf.12318

64. Dietz, T., K. Frank, C. Whitley, J. Kelly, and R. Kelly, 2015: Political influences on greenhouse gas emissions from US States. *Proceedings of the National Academy of Sciences*, **112** (27), 8254–8259. https://doi.org/10.1073/pnas.1417806112

65. IPCC, 2021: Annex VII: Glossary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, S. Semenov, and A. Reisinger, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2215–2256. https://doi.org/10.1017/9781009157896.022

66. Lee, C., 2021: Confronting disproportionate impacts and systemic racism in environmental policy. *Environmental Law Reporter*, **51**, 10207. http://thinkpunkgirl.com/wp-content/uploads/2021/03/Lee_2021.pdf

67. Cusack, L., A. van Loon, D. Kralik, P. Arbon, and S. Gilbert, 2013: Extreme weather-related health needs of people who are homeless. *Australian Journal of Primary Health*, **19** (3), 250–255. https://doi.org/10.1071/py12048

68. Saverino, K.C., E. Routman, T.R. Lookingbill, A.M. Eanes, J.S. Hoffman, and R. Bao, 2021: Thermal inequity in Richmond, VA: The effect of an unjust evolution of the urban landscape on urban heat islands. *Sustainability*, **13** (3), 1511. https://doi.org/10.3390/su13031511

69. Shaw, M., 2004: Housing and public health. *Annual Review of Public Health*, **25** (1), 397–418. https://doi.org/10.1146/annurev.publhealth.25.101802.123036

70. Cox, R.S. and M. Hamlen, 2015: Community disaster resilience and the rural Resilience Index. *American Behavioral Scientist*, **59** (2), 220–237. https://doi.org/10.1177/0002764214550297

71. Jerolleman, A., 2020: Ch. 11. Challenges of post-disaster recovery in rural areas. In: *Louisiana's Response to Extreme Weather: A Coastal State's Adaptation Challenges and Successes*. Laska, S., Ed. Springer, Cham, Switzerland, 285–310. https://doi.org/10.1007/978-3-030-27205-0_11

72. May, P.J., 2013: Ch. 7. Public risks and disaster resilience: Rethinking public and private sector roles. In: *Disaster Resiliency*, 1st ed. Kapucu, N., C.V. Hawkins, and F.I. Rivera, Eds. Routledge, 20. https://doi.org/10.4324/9780203102459

73. Schwab, J., 2016: Planning and climate change: Creating resilience in US communities. In: *Living With Climate Change: How Communities are Surviving and Thriving in a Changing Climate*. Bullock, J., G. Haddow, K. Haddow, and D. Coppola, Eds. CRC Press, Boca Raton, FL, 71–81. https://www.routledge.com/living-with-climate-change-how-communities-are-surviving-and-thriving-in/bullock-haddow-haddow-coppola/p/book/9781498725361

74. Bullard, R.D., 2008: Differential vulnerabilities: Environmental and economic inequality and government response to unnatural disasters. *Social Research: An International Quarterly*, **75** (3), 753–784. https://doi.org/10.1353/sor.2008.0035

75. Hewitt, K., Ed. 1983: *Interpretations of Calamity: From the Viewpoint of Human Ecology*. 1st ed., Routledge, 326 pp. https://doi.org/10.4324/9780429329579

76. Jacobs, F., 2019: Black feminism and radical planning: New directions for disaster planning research. *Planning Theory*, **18** (1), 24–39. https://doi.org/10.1177/1473095218763221

77. Marino, E., 2015: *Fierce Climate, Sacred Ground: An Ethnography of Climate Change in Shishmaref, Alaska*. University of Alaska Press, Fairbanks, AK, 122 pp. https://upcolorado.com/university-of-alaska-press/item/5674-fierce-climate-sacred-ground

78. Oliver-Smith, A., 1996: Anthropological research on hazards and disasters. *Annual Review of Anthropology*, **25** (1), 303–328. https://doi.org/10.1146/annurev.anthro.25.1.303

79. Farbotko, C. and H. Lazrus, 2012: The first climate refugees? Contesting global narratives of climate change in Tuvalu. *Global Environmental Change*, **22** (2), 382–390. https://doi.org/10.1016/j.gloenvcha.2011.11.014

80. Kelman, I., 2015: Climate change and the Sendai Framework for Disaster Risk Reduction. *International Journal of Disaster Risk Science*, **6** (2), 117–127. https://doi.org/10.1007/s13753-015-0046-5

81. U.S. Commission on Civil Rights, 2022: Civil Rights and Protections During the Federal Response to Hurricanes Harvey and Maria. U.S. Commission on Civil Rights, Washington, DC. https://www.usccr.gov/files/2022-09/2022-statutory-report-fema.pdf

82. Kelly, C., K. Costa, and S. Edelman, 2017: Safe, Strong, and Just Rebuilding After Hurricanes Harvey, Irma, and Maria: A Policy Road Map for Congress. Center for American Progress. https://www.americanprogress.org/article/safe-strong-just-rebuilding-hurricanes-harvey-irma-maria/

83. Maxwell, C., 2018: America's Sordid Legacy on Race and Disaster Recovery. Center for American Progress. https://www.americanprogress.org/article/americas-sordid-legacy-race-disaster-recovery/

84. Bier, V.M., 2017: Understanding and mitigating the impacts of massive relocations due to disasters. *Economics of Disasters and Climate Change*, **1** (2), 179–202. https://doi.org/10.1007/s41885-017-0003-4

85. Azar, D. and D. Rain, 2007: Identifying population vulnerable to hydrological hazards in San Juan, Puerto Rico. *GeoJournal*, **69** (1), 23–43. https://doi.org/10.1007/s10708-007-9106-8

86. Hannah, M.G., 2001: Sampling and the politics of representation in US Census 2000. *Environment and Planning D: Society and Space*, **19** (5), 515–534. https://doi.org/10.1068/d289

87. Morey, B.N., A. Tulua, S.P. Tanjasiri, A.M. Subica, J.K.a. Kaholokula, C. Penaia, K. Thomas, R.C. Chang, V.D. Tran, N.A. Ponce, P. Ong, and E. Ong, 2020: Structural racism and its effects on Native Hawaiians and Pacific Islanders in the United States: Issues of health equity, census undercounting, and voter disenfranchisement. *AAPI Nexus: Policy, Practice and Community*, **17** (1–2). https://www.aapinexus.org/2020/11/24/structural-racism-and-its-effects-on-native-hawaiians-and-pacific-islanders/

88. Hardy, R.D., R.A. Milligan, and N. Heynen, 2017: Racial coastal formation: The environmental injustice of colorblind adaptation planning for sea-level rise. *Geoforum*, **87**, 62–72. https://doi.org/10.1016/j.geoforum.2017.10.005

89. IPCC, 2022: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844

90. Marino, E. and J. Ribot, 2012: Special issue introduction: Adding insult to injury: Climate change and the inequities of climate intervention. *Global Environmental Change*, **22** (2), 323–328. https://doi.org/10.1016/j.gloenvcha.2012.03.001

91. Shrader-Frechette, K., 2002: *Environmental Justice: Creating Equity, Reclaiming Democracy*. Oxford University Press. https://doi.org/10.1093/0195152034.001.0001

92. Farmer, P., 2004: An anthropology of structural violence. *Current Anthropology*, **45** (3), 305–325. https://doi.org/10.1086/382250

93. Soron, D., 2007: Cruel weather: Natural disasters and structural violence. *Transformations: Journal of Media and Culture*, **14** (1). http://www.transformationsjournal.org/wp-content/uploads/2017/01/Soron_Transformations14.pdf

94. Jones-DeWeever, A.W., and H. Hartmann, 2006: Ch. 5. Abandoned before the storms: The glaring disaster of gender, race, and class disparities in the Gulf. In: *There's No Such Thing as a Natural Disaster: Race, Class and Katrina*. Hartman, C. and G.D. Squires, Eds. Taylor & Francis, New York, 17. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203625460-5/abandoned-storms-avis-jones-deweever-heidi-hartmann

95. Bronen, R., 2010: Ch. 7. Forced migration of Alaskan indigenous communities due to climate change. In: *Environment, Forced Migration and Social Vulnerability*. Afifi, T. and J. Jäger, Eds. Springer, Berlin, Heidelberg, 87–98. https://doi.org/10.1007/978-3-642-12416-7_7

96. Comardelle, C., 2020: Preserving our place: Isle de Jean Charles. *Nonprofit Quarterly*. https://nonprofitquarterly.org/preserving-our-place-isle-de-jean-charles/

97. Termeer, C.J.A.M., A. Dewulf, S.I. Karlsson-Vinkhuyzen, M. Vink, and M. van Vliet, 2016: Coping with the wicked problem of climate adaptation across scales: The five R governance capabilities. *Landscape and Urban Planning*, **154**, 11–19. https://doi.org/10.1016/j.landurbplan.2016.01.007

98. Madison, J., 1788: The Structure of the Government Must Furnish the Proper Checks and Balances Between the Different Departments. The Federalist Papers: No. 51. Publius. https://guides.loc.gov/federalist-papers/text-51-60

99. FEMA, 2022: Teamwork Approach to Outreach and Engagement Reduces Flood Risk. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/case-study/teamwork-approach-outreach-and-engagement-reduces-flood-risk

100. City of Tulsa, 2023: Flooding History. City of Tulsa. https://www.cityoftulsa.org/government/departments/engineering-services/flood-control/flooding-history/

101. Vogel, J., K.M. Carney, J.B. Smith, C. Herrick, M. Stults, M. O'Grady, A.S. Juliana, H. Hosterman, and L. Giangola, 2016: Climate Adaptation: The State of Practice in U.S. Communities. The Kresge Foundation. https://kresge.org/resource/climate-adaptation-the-state-of-practice-in-u-s-communities/

102. Faas, A.J., 2022: *In the Shadow of Tungurahua: Disaster Politics in Highland Ecuador*. Rutgers University Press, 246 pp. https://www.rutgersuniversitypress.org/in-the-shadow-of-tungurahua/9781978831568

103. Hulme, M., 2015: Climate and its changes: A cultural appraisal. *Geo: Geography and Environment*, **2** (1), 1–11. https://doi.org/10.1002/geo2.5

104. Agrawal, A., 2005: *Environmentality: Technologies of Government and the Making of Subjects*. Duke University Press, Durham, NC, 344 pp. https://www.dukeupress.edu/environmentality

105. Coen, D.R., 2021: A brief history of usable climate science. *Climatic Change*, **167** (3), 51. https://doi.org/10.1007/s10584-021-03181-2

106. Hulme, M., 2009: *Why We Disagree About Climate Change: Understanding Controversy, Inaction and Opportunity*. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/cbo9780511841200

107. Jasanoff, S., 2010: A new climate for society. *Theory, Culture & Society*, **27** (2–3), 233–253. https://doi.org/10.1177/0263276409361497

108. Masco, J., 2010: Bad weather: On planetary crisis. *Social Studies of Science*, **40** (1), 7–40. https://doi.org/10.1177/0306312709341598

109. Neale, T. and D. May, 2020: Fuzzy boundaries: Simulation and expertise in bushfire prediction. *Social Studies of Science*, **50** (6), 837–859. https://doi.org/10.1177/0306312720906869

110. Petryna, A., 2022: *Horizon Work: At the Edges of Knowledge in an Age of Runaway Climate Change*. Princeton University Press, 224 pp. https://press.princeton.edu/books/hardcover/9780691211664/horizon-work

111. Ulturgasheva, O. and B. Bodenhorn, Eds., 2022: *Risky Futures: Climate, Geopolitics and Local Realities in the Uncertain Circumpolar North*. Vol. 6. Berghahn Books, 234 pp. https://doi.org/10.3167/9781800735934

112. Vaughn, S.E., 2022: *Engineering Vulnerability: In Pursuit of Climate Adaptation*. Duke University Press, 272 pp. https://www.dukeupress.edu/engineering-vulnerability

113. ICC Alaska, 2015: Alaskan Inuit Food Security Conceptual Framework: How to Assess the Arctic from an Inuit Perspective. Inuit Circumpolar Council, Alaska, 116 pp. https://iccalaska.org/wp-icc/wp-content/uploads/2016/05/Food-Security-Full-Technical-Report.pdf

114. Callison, C., 2014: *How Climate Change Comes to Matter: The Communal Life of Facts*. Duke University Press, 328 pp. https://www.dukeupress.edu/how-climate-change-comes-to-matter

115. Felt, U., R. Fouché, C.A. Miller, and L. Smith-Doerr, Eds., 2016: *The Handbook of Science and Technology Studies*. 4th ed., MIT Press, 1208 pp. https://mitpress.mit.edu/9780262035682/the-handbook-of-science-and-technology-studies/

116. Kimmerer, R.W., 2015: *Braiding Sweetgrass: Indigenous Wisdom, Scientific Knowledge, and the Teachings of Plants*. Milkweed Editions, 408 pp. https://milkweed.org/book/braiding-sweetgrass

117. McGregor, D., 2004: Coming full circle: Indigenous Knowledge, environment, and our future. *The American Indian Quarterly*, **28**, 385–410. https://doi.org/10.1353/aiq.2004.0101

118. McGregor, D., S. Whitaker, and M. Sritharan, 2020: Indigenous environmental justice and sustainability. *Current Opinion in Environmental Sustainability*, **43**, 35–40. https://doi.org/10.1016/j.cosust.2020.01.007

119. Whyte, K., 2018: Settler colonialism, ecology, and environmental injustice. *Environment and Society*, **9** (1), 125–144. https://doi.org/10.3167/ares.2018.090109

120. Wildcat, D.R., 2013: Introduction: Climate change and Indigenous peoples of the USA. *Climatic Change*, **120** (3), 509–515. https://doi.org/10.1007/s10584-013-0849-6

121. Fahey, D.W., S. Doherty, K.A. Hibbard, A. Romanou, and P.C. Taylor, 2017: Ch. 2. Physical drivers of climate change. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 73–113. https://doi.org/10.7930/j0513wcr

122. Callison, C., 2021: Refusing more empire: Utility, colonialism, and Indigenous knowing. *Climatic Change*, **167** (3), 58. https://doi.org/10.1007/s10584-021-03188-9

123. Cochran, P., O.H. Huntington, C. Pungowiyi, S. Tom, F.S. Chapin, III, H.P. Huntington, N.G. Maynard, and S.F. Trainor, 2013: Indigenous frameworks for observing and responding to climate change in Alaska. *Climatic Change*, **120** (3), 557–567. https://doi.org/10.1007/s10584-013-0735-2

124. Erickson, B., 2020: Anthropocene futures: Linking colonialism and environmentalism in an age of crisis. *Environment and Planning D: Society and Space*, **38** (1), 111–128. https://doi.org/10.1177/0263775818806514

125. Maldonado, J.K., C. Shearer, R. Bronen, K. Peterson, and H. Lazrus, 2013: The impact of climate change on tribal communities in the US: Displacement, relocation, and human rights. *Climatic Change*, **120** (3), 601–614. https://doi.org/10.1007/s10584-013-0746-z

126. Malm, A., 2016: *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming*. Verso Books, 496 pp. https://www.versobooks.com/books/2002-fossil-capital

127. Reo, N.J. and A.K. Parker, 2014: Ch. 13. Re-thinking colonialism to prepare for the impacts of rapid environmental change. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., B. Colombi, and R. Pandya, Eds. Springer, Cham, Switzerland, 163–174. https://doi.org/10.1007/978-3-319-05266-3_13

128. Smith, H.A. and K. Sharp, 2012: Indigenous climate knowledges. *WIREs Climate Change*, **3** (5), 467–476. https://doi.org/10.1002/wcc.185

129. Beer, C.T., 2022: "Systems change not climate change": Support for a radical shift away from capitalism at mainstream U.S. climate change protest events. *The Sociological Quarterly*, **63** (1), 175–198. https://doi.org/10.1080/00380253.2020.1842141

130. Coombes, B., J.T. Johnson, and R. Howitt, 2013: Indigenous geographies II: The aspirational spaces in postcolonial politics—Reconciliation, belonging and social provision. *Progress in Human Geography*, **37** (5), 691–700. https://doi.org/10.1177/0309132512469590

131. Gram-Hanssen, I., N. Schafenacker, and J. Bentz, 2022: Decolonizing transformations through 'right relations'. *Sustainability Science*, **17** (2), 673–685. https://doi.org/10.1007/s11625-021-00960-9

132. Latour, B., I. Stengers, A. Tsing, and N. Bubandt, 2018: Anthropologists are talking—About capitalism, ecology, and apocalypse. *Ethnos*, **83** (3), 587–606. https://doi.org/10.1080/00141844.2018.1457703

133. Moore, J.W., 2018: The Capitalocene Part II: Accumulation by appropriation and the centrality of unpaid work/energy. *The Journal of Peasant Studies*, **45** (2), 237–279. https://doi.org/10.1080/03066150.2016.1272587

134. van Dooren, T., E. Kirksey, and U. Münster, 2016: Multispecies studies: Cultivating arts of attentiveness. *Environmental Humanities*, **8** (1), 1–23. https://doi.org/10.1215/22011919-3527695

135. Wildcat, D.R., 2010: *Red Alert!: Saving the Planet with Indigenous Knowledge*. Fulcrum Publishing. https://birchbarkbooks.com/products/red-alert

136. Makondo, C.C. and D.S.G. Thomas, 2018: Climate change adaptation: Linking indigenous knowledge with western science for effective adaptation. *Environmental Science & Policy*, **88**, 83–91. https://doi.org/10.1016/j.envsci.2018.06.014

137. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

138. Bremer, S. and S. Meisch, 2017: Co-production in climate change research: Reviewing different perspectives. *WIREs Climate Change*, **8** (6), e482. https://doi.org/10.1002/wcc.482

139. Jasanoff, S., 2004: *States of Knowledge: The Co-Production of Science and the Social Order*, 1st ed. Routledge, 332 pp. https://www.routledge.com/states-of-knowledge-the-co-production-of-science-and-the-social-order/jasanoff/p/book/9780415403290

140. Meadow, A.M., D.B. Ferguson, Z. Guido, A. Horangic, G. Owen, and T. Wall, 2015: Moving toward the deliberate coproduction of climate science knowledge. *Weather, Climate, and Society*, **7** (2), 179–191. https://doi.org/10.1175/wcas-d-14-00050.1

141. David-Chavez, D.M. and M.C. Gavin, 2018: A global assessment of Indigenous community engagement in climate research. *Environmental Research Letters*, **13** (12), 123005. https://doi.org/10.1088/1748-9326/aaf300

142. Miner, K., L. Canavera, J. Gonet, K. Luis, M. Maddox, P. McCarney, G. Bridge, D. Schimel, and J. Rattlingleaf, 2023: The co-production of knowledge for climate science. *Nature Climate Change*, **13** (4), 307–308. https://doi.org/10.1038/s41558-023-01633-4

143. Ellam Yua, J. Raymond-Yakoubian, R. Aluaq Daniel, and C. Behe, 2022: A framework for co-production of knowledge in the context of Arctic research. *Ecology and Society*, **27** (1), 34. https://doi.org/10.5751/es-12960-270134

144. Kahan, D., 2012: Why we are poles apart on climate change. *Nature*, **488**, 255. https://doi.org/10.1038/488255a

145. Leiserowitz, A., E. Maibach, C. Roser-Renouf, G. Feinberg, and S. Rosenthal, 2016: Climate Change in the American Mind. Yale Program on Climate Change and George Mason University, Center for Climate Change Communication, New Haven, CT. https://climatecommunication.yale.edu/publications/climate-change-american-mind-march-2016/

146. Hornsey, M.J., E.A. Harris, P.G. Bain, and K.S. Fielding, 2016: Meta-analyses of the determinants and outcomes of belief in climate change. *Nature Climate Change*, **6** (6), 622–626. https://doi.org/10.1038/nclimate2943

147. McCright, A.M., S.T. Marquart-Pyatt, R.L. Shwom, S.R. Brechin, and S. Allen, 2016: Ideology, capitalism, and climate: Explaining public views about climate change in the United States. *Energy Research & Social Science*, **21**, 180–189. https://doi.org/10.1016/j.erss.2016.08.003

148. Pearson, A.R., M.T. Ballew, S. Naiman, and J.P. Schuldt, 2017: Race, class, gender and climate change communication. In: *Oxford Encyclopedia of Climate Change Communication*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.412

149. Almiron, N. and J. Xifra, Eds., 2020: *Climate Change Denial and Public Relations: Strategic Communication and Interest Groups in Climate Inaction*. 1st ed., Taylor & Francis, London, UK, 268 pp. https://doi.org/10.4324/9781351121798

150. Dunlap, R.E., R.J. Brulle, D.C. Holmes, and L.M. Richardson, 2020: Ch. 6. Sources and amplifiers of climate change denial. In: *Research Handbook on Communicating Climate Change*. Holmes, D.C. and L.M. Richardson, Eds. Edward Elgar Publishing, 49–61. https://doi.org/10.4337/9781789900408.00013

151. Dunlap, R.E. and A.M. McCright, 2011: Ch. 10. Organized climate change denial. In: *The Oxford Handbook of Climate Change and Society*. Dryzek, J.S., R.B. Norgaard, and D. Schlosberg, Eds. Oxford University Press, 144–160. https://doi.org/10.1093/oxfordhb/9780199566600.003.0010

152. Oreskes, N. and E.M. Conway, 2010: Defeating the merchants of doubt. *Nature*, **465** (7299), 686–687. https://doi.org/10.1038/465686a

153. Markowitz, E.M. and M.L. Guckian, 2018: Ch. 3. Climate change communication: Challenges, insights, and opportunities. In: *Psychology and Climate Change*. Clayton, S. and C. Manning, Eds. Academic Press, 35–63. https://doi.org/10.1016/b978-0-12-813130-5.00003-5

154. Corner, A., C. Shaw, and J. Clarke, 2018: Principles for Effective Communication and Public Engagement on Climate Change: A Handbook for IPCC Authors. Climate Outreach, Oxford, UK. https://www.ipcc.ch/site/assets/uploads/2017/08/Climate-Outreach-IPCC-communications-handbook.pdf

155. Hine, D.W., W.J. Phillips, R. Cooksey, J.P. Reser, P. Nunn, A.D. Marks, N.M. Loi, and S.E. Watt, 2016: Preaching to different choirs: How to motivate dismissive, uncommitted, and alarmed audiences to adapt to climate change? *Global Environmental Change*, **36**, 1–11. https://doi.org/10.1016/j.gloenvcha.2015.11.002

156. Dietz, T., 2013: Bringing values and deliberation to science communication. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (Supplement_3), 14081–14087. https://doi.org/10.1073/pnas.1212740110

157. Brulle, R.J., 2010: From environmental campaigns to advancing the public dialog: Environmental communication for civic engagement. *Environmental Communication*, **4** (1), 82–98. https://doi.org/10.1080/17524030903522397

158. Howarth, C., L. Parsons, and H. Thew, 2020: Effectively communicating climate science beyond academia: Harnessing the heterogeneity of climate knowledge. *One Earth*, **2** (4), 320–324. https://doi.org/10.1016/j.oneear.2020.04.001

159. Pathak, M., J. Roy, S. Patel, S. Some, P. Vyas, N. Das, and P. Shukla, 2021: Communicating climate change findings from IPCC reports: Insights from outreach events in India. *Climatic Change*, **168**, 23. https://doi.org/10.1007/s10584-021-03224-8

160. Geiger, N., K. Gasper, J.K. Swim, and J. Fraser, 2019: Untangling the components of hope: Increasing pathways (not agency) explains the success of an intervention that increases educators' climate change discussions. *Journal of Environmental Psychology*, **66**, 101366. https://doi.org/10.1016/j.jenvp.2019.101366

161. Swim, J.K. and J. Fraser, 2013: Fostering hope in climate change educators. *Journal of Museum Education*, **38** (3), 286–297. https://doi.org/10.1080/10598650.2013.11510781

162. Asensio, O.I. and M.A. Delmas, 2015: Nonprice incentives and energy conservation. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (6), 510–515. https://doi.org/10.1073/pnas.1401880112

163. CRED and ecoAmerica, 2014: Connecting on Climate: A Guide to Effective Climate Change Communication. Center for Research on Environmental Decisions and ecoAmerica, New York and Washington, DC. https://ecoamerica.org/wp-content/uploads/2014/12/ecoAmerica-CRED-2014-Connecting-on-Climate.pdf

164. Gromet, D.M., H. Kunreuther, and R.P. Larrick, 2013: Political ideology affects energy-efficiency attitudes and choices. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (23), 9314–9319. https://doi.org/10.1073/pnas.1218453110

165. Corner, A., O. Roberts, S. Chiari, S. Völler, E.S. Mayrhuber, S. Mandl, and K. Monson, 2015: How do young people engage with climate change? The role of knowledge, values, message framing, and trusted communicators. *Wiley Interdisciplinary Reviews: Climate Change*, **6** (5), 523–534. https://doi.org/10.1002/wcc.353

166. Goldberg, M.H., A. Gustafson, S.A. Rosenthal, and A. Leiserowitz, 2021: Shifting Republican views on climate change through targeted advertising. *Nature Climate Change*, **11**, 573–577. https://doi.org/10.1038/s41558-021-01070-1

167. Lawson, D.F., K.T. Stevenson, M.N. Peterson, S.J. Carrier, R. L. Strnad, and E. Seekamp, 2019: Children can foster climate change concern among their parents. *Nature Climate Change*, **9** (6), 458–462. https://doi.org/10.1038/s41558-019-0463-3

168. Ho, E.H., D.V. Budescu, and H.H. Por, 2017: Psychological challenges in communicating about climate change and its uncertainties. In: *Oxford Research Encyclopedia of Climate Science*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.381

169. Budescu, D.V., H.-H. Por, and S.B. Broomell, 2012: Effective communication of uncertainty in the IPCC reports. *Climatic Change*, **113** (2), 181–200. https://doi.org/10.1007/s10584-011-0330-3

170. Stephens, E.M., T.L. Edwards, and D. Demeritt, 2012: Communicating probabilistic information from climate model ensembles—Lessons from numerical weather prediction. *WIREs Climate Change*, **3** (5), 409–426. https://doi.org/10.1002/wcc.187

171. Howe, L., B. MacInnis, J.A. Krosnick, E.M. Markowitz, and R. Socolow, 2019: Acknowledging uncertainty impacts public acceptance of climate scientists' predictions. *Nature Climate Change*, **9**, 863–867. https://doi.org/10.1038/s41558-019-0587-5

172. Bergquist, M., M. Thiel, M.H. Goldberg, and S. van der Linden, 2023: Field interventions for climate change mitigation behaviors: A second-order meta-analysis. *Proceedings of the National Academy of Sciences of the United States of America*, **120** (13), e2214851120. https://doi.org/10.1073/pnas.2214851120

173. Nisa, C.F., J.J. Bélanger, B.M. Schumpe, and D.G. Faller, 2019: Meta-analysis of randomised controlled trials testing behavioural interventions to promote household action on climate change. *Nature Communications*, **10** (1), 4545. https://doi.org/10.1038/s41467-019-12457-2

174. Orlove, B., R. Shwom, E. Markowitz, and S.-M. Cheong, 2020: Climate decision-making. *Annual Review of Environment and Resources*, **45** (1), 271–303. https://doi.org/10.1146/annurev-environ-012320-085130

175. Kumpu, V., 2022: What is public engagement and how does it help to address climate change? A review of climate communication research. *Environmental Communication*, **16** (3), 304–316. https://doi.org/10.1080/17524032.2022.2055601

176. Cialdini, R.B. and R.P. Jacobson, 2021: Influences of social norms on climate change-related behaviors. *Current Opinion in Behavioral Sciences*, **42**, 1–8. https://doi.org/10.1016/j.cobeha.2021.01.005

177. Ruano-Chamorro, C., G.G. Gurney, and J.E. Cinner, 2022: Advancing procedural justice in conservation. *Conservation Letters*, **15** (3), e12861. https://doi.org/10.1111/conl.12861

178. Black, R., W.N. Adger, N.W. Arnell, S. Dercon, A. Geddes, and D. Thomas, 2011: The effect of environmental change on human migration. *Global Environmental Change*, **21**, S3–S11. https://doi.org/10.1016/j.gloenvcha.2011.10.001

179. Black, R., S.R.G. Bennett, S.M. Thomas, and J.R. Beddington, 2011: Migration as adaptation. *Nature*, **478** (7370), 447–449. https://doi.org/10.1038/478477a

180. Ihrke, D., 2014: Reason for Moving: 2012 to 2013. P20-574. U.S. Census Bureau, 15 pp. https://www.census.gov/content/dam/Census/library/publications/2014/demo/p20-574.pdf

181. Lee, B.A. and M. Evans, 2020: Forced to move: Patterns and predictors of residential displacement during an era of housing insecurity. *Social Science Research*, **87**, 102415. https://doi.org/10.1016/j.ssresearch.2020.102415

182. Elliott, J.R., 2015: Natural hazards and residential mobility: General patterns and racially unequal outcomes in the United States. *Social Forces*, **93** (4), 1723–1747. https://doi.org/10.1093/sf/sou120

183. Fussell, E., S.R. Curran, M.D. Dunbar, M.A. Babb, L. Thompson, and J. Meijer-Irons, 2017: Weather-related hazards and population change: A study of hurricanes and tropical storms in the United States, 1980–2012. *The ANNALS of the American Academy of Political and Social Science*, **669** (1), 146–167. https://doi.org/10.1177/0002716216682942

184. Logan, J.R., S. Issar, and Z. Xu, 2016: Trapped in place? Segmented resilience to hurricanes in the Gulf Coast, 1970–2005. *Demography*, **53** (5), 1511–1534. https://doi.org/10.1007/s13524-016-0496-4

185. Raker, E.J., 2020: Natural hazards, disasters, and demographic change: The case of severe tornadoes in the United States, 1980–2010. *Demography*, **57** (2), 653–674. https://doi.org/10.1007/s13524-020-00862-y

186. Fussell, E. and B. Castro, 2022: Ch. 10. Environmentally informed migration in North America. In: *International Handbook of Population and Environment*. Hunter, L.M., C. Gray, and J. Véron, Eds. Springer, Cham, Switzerland, 205–223. https://doi.org/10.1007/978-3-030-76433-3_10

187. Gutmann, M.P. and V. Field, 2010: Katrina in historical context: Environment and migration in the U.S. *Population and Environment*, **31** (1), 3–19. https://doi.org/10.1007/s11111-009-0088-y

188. Rappaport, J. and J.D. Sachs, 2003: The United States as a coastal nation. *Journal of Economic Growth*, **8** (1), 5–46. https://doi.org/10.1023/a:1022870216673

189. Dronkers, J., J.T.E. Gilbert, L.W. Butler, J.J. Carey, J. Campbell, E. James, C. McKenzie, R. Misdorp, N. Quin, K.L. Ries, P.C. Schroder, J.R. Spradley, J.G. Titus, L. Vallianos, and J. von Dadelszen, 1990: *Strategies for Adaptation to Sea Level Rise. Report of the IPCC Coastal Zone Management Subgroup*. Intergovernmental Panel on Climate Change, Geneva, Switzerland. https://www.ipcc.ch/publication/strategies-for-adaptation-to-sea-level-rise/

190. Ratter, B. and C. Leyshon, 2021: Perceptions of and resilience to coastal climate risks. In: *Oxford Research Encyclopedia of Climate Science*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.819

191. Acosta, R.J., N. Kishore, R.A. Irizarry, and C.O. Buckee, 2020: Quantifying the dynamics of migration after Hurricane Maria in Puerto Rico. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (51), 32772–32778. https://doi.org/10.1073/pnas.2001671117

192. Curtis, K.J., J. DeWaard, E. Fussell, and R.A. Rosenfeld, 2020: Differential recovery migration across the rural–urban gradient: Minimal and short-term population gains for rural disaster-affected Gulf Coast counties. *Rural Sociology*, **85** (4), 856–898. https://doi.org/10.1111/ruso.12305

193. Curtis, K.J., E. Fussell, and J. DeWaard, 2015: Recovery migration after Hurricanes Katrina and Rita: Spatial concentration and intensification in the migration system. *Demography*, **52** (4), 1269–1293. https://doi.org/10.1007/s13524-015-0400-7

194. DeWaard, J., J.E. Johnson, and S.D. Whitaker, 2020: Out-migration from and return migration to Puerto Rico after Hurricane Maria: Evidence from the consumer credit panel. *Population and Environment*, **42** (1), 28–42. https://doi.org/10.1007/s11111-020-00339-5

195. Fussell, E., 2015: The long-term recovery of New Orleans' population after Hurricane Katrina. *American Behavioral Scientist*, **59** (10), 1231–1245. https://doi.org/10.1177/0002764215591181

196. Fussell, E., N. Sastry, and M. VanLandingham, 2010: Race, socioeconomic status, and return migration to New Orleans after Hurricane Katrina. *Population and Environment*, **31** (1), 20–42. https://doi.org/10.1007/s11111-009-0092-2

197. McConnell, K., S.D. Whitaker, E. Fussell, J. DeWaard, K. Curtis, K. Price, L.S. Denis, and J. Balch, 2021: Effects of Wildfire Destruction on Migration, Consumer Credit, and Financial Distress. Working Paper No. 21-29. Federal Reserve Bank of Cleveland. https://doi.org/10.26509/frbc-wp-202129

198. Santos-Lozada, A.R., M. Kaneshiro, C. McCarter, and M. Marazzi-Santiago, 2020: Puerto Rico exodus: Long-term economic headwinds prove stronger than Hurricane Maria. *Population and Environment*, **42** (1), 43–56. https://doi.org/10.1007/s11111-020-00355-5

199. Schultz, J. and J.R. Elliott, 2013: Natural disasters and local demographic change in the United States. *Population and Environment*, **34** (3), 293–312. https://doi.org/10.1007/s11111-012-0171-7

200. Cohen, D., 2019: 94.7M Americans Live in Coastline Regions: About 60.2 Million Live in Areas Most Vulnerable to Hurricanes. U.S. Census Bureau. https://www.census.gov/library/stories/2019/07/millions-of-americans-live-coastline-regions.html

201. Hauer, M.E., E. Fussell, V. Mueller, M. Burkett, M. Call, K. Abel, R. McLeman, and D. Wrathall, 2020: Sea-level rise and human migration. *Nature Reviews Earth & Environment*, **1** (1), 28–39. https://doi.org/10.1038/s43017-019-0002-9

202. Xu, C., T.A. Kohler, T.M. Lenton, J.C. Svenning, and M. Scheffer, 2020: Future of the human climate niche. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (21), 11350–11355. https://doi.org/10.1073/pnas.1910114117

203. Peacock, W.G., S. Van Zandt, Y. Zhang, and W.E. Highfield, 2014: Inequities in long-term housing recovery after disasters. *Journal of the American Planning Association*, **80** (4), 356–371. https://doi.org/10.1080/01944363.2014.980440

204. Green, T.F. and R.B. Olshansky, 2012: Rebuilding housing in New Orleans: The Road Home Program after the Hurricane Katrina disaster. *Housing Policy Debate*, **22** (1), 75–99. https://doi.org/10.1080/10511482.2011.624530

205. Greer, A., S.B. Binder, A. Thiel, M. Jamali, and A. Nejat, 2020: Place attachment in disaster studies: Measurement and the case of the 2013 Moore tornado. *Population and Environment*, **41** (3), 306–329. https://doi.org/10.1007/s11111-019-00332-7

206. Peacock, W.G., N. Dash, Y. Zhang, and S. Van Zandt, 2018: Ch. 27. Post-disaster sheltering, temporary housing and permanent housing recovery. In: *Handbook of Disaster Research*. Rodríguez, H., W. Donner, and J.E. Trainor, Eds. Springer, Cham, Switzerland, 569–594. https://doi.org/10.1007/978-3-319-63254-4_27

207. Lee, J.Y. and S. Van Zandt, 2019: Housing tenure and social vulnerability to disasters: A review of the evidence. *Journal of Planning Literature*, **34** (2), 156–170. https://doi.org/10.1177/0885412218812080

208. Charles, C.Z., 2003: The dynamics of racial residential segregation. *Annual Review of Sociology*, **29** (1), 167–207. https://doi.org/10.1146/annurev.soc.29.010202.100002

209. Tate, E., M.A. Rahman, C.T. Emrich, and C.C. Sampson, 2021: Flood exposure and social vulnerability in the United States. *Natural Hazards*, **106** (1), 435–457. https://doi.org/10.1007/s11069-020-04470-2

210. Burby, R.J., L.J. Steinberg, and V. Basolo, 2003: The tenure trap: The vulnerability of renters to joint natural and technological disasters. *Urban Affairs Review*, **39** (1), 32–58. https://doi.org/10.1177/1078087403253053

211. Dundon, L.A. and J.S. Camp, 2021: Climate justice and home-buyout programs: Renters as a forgotten population in managed retreat actions. *Journal of Environmental Studies and Sciences*, **11**, 420–433. https://doi.org/10.1007/s13412-021-00691-4

212. Fussell, E. and E. Harris, 2014: Homeownership and housing displacement after Hurricane Katrina among low-income African-American mothers in New Orleans. *Social Science Quarterly*, **95** (4), 1086–1100. https://doi.org/10.1111/ssqu.12114

213. Lim, J., S. Loveridge, R. Shupp, and M. Skidmore, 2017: Double danger in the double wide: Dimensions of poverty, housing quality and tornado impacts. *Regional Science and Urban Economics*, **65**, 1–15. https://doi.org/10.1016/j.regsciurbeco.2017.04.003

214. Zhang, Y. and W.G. Peacock, 2009: Planning for housing recovery? Lessons learned from Hurricane Andrew. *Journal of the American Planning Association*, **76** (1), 5–24. https://doi.org/10.1080/01944360903294556

215. Gotham, K.F., 2014: Reinforcing inequalities: The impact of the CDBG program on post-Katrina rebuilding. *Housing Policy Debate*, **24** (1), 192–212. https://doi.org/10.1080/10511482.2013.840666

216. Wilson, B., E. Tate, and C.T. Emrich, 2021: Flood recovery outcomes and disaster assistance barriers for vulnerable populations. *Frontiers in Water*, **3**, 752307. https://doi.org/10.3389/frwa.2021.752307

217. Hamideh, S., W.G. Peacock, and S. Van Zandt, 2021: Housing type matters for pace of recovery: Evidence from Hurricane Ike. *International Journal of Disaster Risk Reduction*, **57**, 102149. https://doi.org/10.1016/j.ijdrr.2021.102149

218. Elliott, J.R. and J. Howell, 2017: Beyond disasters: A longitudinal analysis of natural hazards' unequal impacts on residential instability. *Social Forces*, **95** (3), 1181–1207. https://doi.org/10.1093/sf/sow086

219. Elliott, J.R. and J. Pais, 2006: Race, class, and Hurricane Katrina: Social differences in human responses to disaster. *Social Science Research*, **35** (2), 295–321. https://doi.org/10.1016/j.ssresearch.2006.02.003

220. Lamba-Nieves, D. and R. Santiago-Bartolomei, 2022: Who gets emergency housing relief? An analysis of FEMA individual assistance data after Hurricane María. *Housing Policy Debate*, **33** (5), 1146–1166. https://doi.org/10.1080/10511482.2022.2055612

221. Aune, K.T., D. Gesch, and G.S. Smith, 2020: A spatial analysis of climate gentrification in Orleans Parish, Louisiana post-Hurricane Katrina. *Environmental Research*, **185**, 109384. https://doi.org/10.1016/j.envres.2020.109384

222. Bezgrebelna, M., K. McKenzie, S. Wells, A. Ravindran, M. Kral, J. Christensen, V. Stergiopoulos, S. Gaetz, and S.A. Kidd, 2021: Climate change, weather, housing precarity, and homelessness: A systematic review of reviews. *International Journal of Environmental Research and Public Health*, **18** (11), 5812. https://doi.org/10.3390/ijerph18115812

223. Brennan, M., T. Srini, J. Steil, M. Mazereeuw, and L. Ovalles, 2022: A perfect storm? Disasters and evictions. *Housing Policy Debate*, **32** (1), 52–83. https://doi.org/10.1080/10511482.2021.1942131

224. Barile, J.P., S.B. Binder, and C.K. Baker, 2020: Recovering after a natural disaster: Differences in quality of life across three communities after Hurricane Sandy. *Applied Research in Quality of Life*, **15** (4), 1151–1159. https://doi.org/10.1007/s11482-019-09722-3

225. Koslov, L., 2016: The case for retreat. *Public Culture*, **28** (2), 359–387. https://doi.org/10.1215/08992363-3427487

226. Siders, A.R., 2017: Past US floods give lessons in retreat. *Nature*, **548** (7667), 281–281. https://doi.org/10.1038/548281c

227. Binder, S.B. and A. Greer, 2016: The devil is in the details: Linking home buyout policy, practice, and experience after Hurricane Sandy. *Politics and Governance*, **4** (4), 97–106. https://doi.org/10.17645/pag.v4i4.738

228. Siders, A.R., 2019: Social justice implications of US managed retreat buyout programs. *Climatic Change*, **152** (2), 239–257. https://doi.org/10.1007/s10584-018-2272-5

229. Elliott, J.R., P.L. Brown, and K. Loughran, 2020: Racial inequities in the federal buyout of flood-prone homes: A nationwide assessment of environmental adaptation. *Socius*, **6**, 2378023120905439. https://doi.org/10.1177/2378023120905439

230. GAO, 2020: A Climate Migration Pilot Program Could Enhance the Nation's Resilience and Reduce Federal Fiscal Exposure. GAO-20-488. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-20-488.pdf

231. Brody, S.D. and W.E. Highfield, 2013: Open space protection and flood mitigation: A national study. *Land Use Policy*, **32**, 89–95. https://doi.org/10.1016/j.landusepol.2012.10.017

232. Foster, J., A. Lowe, and S. Winkelman, 2011: The Value of Green Infrastructure for Urban Climate Adaptation. The Center for Clean Air Policy. https://savetherain.us/wp-content/uploads/2011/10/Green_Infrastructure_Urban_Climate_Adaptation.pdf

233. Gill, S.E., J.F. Handley, A.R. Ennos, and S. Pauleit, 2007: Adapting cities for climate change: The role of the green infrastructure. *Built Environment*, **33** (1), 115–133. https://doi.org/10.2148/benv.33.1.115

234. Opperman, J.J., G.E. Galloway, J. Fargione, J.F. Mount, B.D. Richter, and S. Secchi, 2009: Sustainable floodplains through large-scale reconnection to rivers. *Science*, **326** (5959), 1487–1488. https://doi.org/10.1126/science.1178256

235. Young, R.F., 2011: Planting the living city: Best practices in planning green infrastructure—Results from major U.S. cities. *Journal of the American Planning Association*, **77** (4), 368–381. https://doi.org/10.1080/01944363.2011.616996

236. Wolch, J.R., J. Byrne, and J.P. Newell, 2014: Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landscape and Urban Planning*, **125**, 234–244. https://doi.org/10.1016/j.landurbplan.2014.01.017

237. Cha, J.M., 2020: A just transition for whom? Politics, contestation, and social identity in the disruption of coal in the Powder River Basin. *Energy Research and Social Science*, **69**, 101657. https://doi.org/10.1016/j.erss.2020.101657

238. Heffron, R.J., 2022: Ch. 2. What is the "just transition"? In: *Achieving a Just Transition to a Low-Carbon Economy*. Palgrave Macmillan, Cham, Switzerland, 9–19. https://doi.org/10.1007/978-3-030-89460-3_2

239. Tessum, C.W., J.S. Apte, A.L. Goodkind, N.Z. Muller, K.A. Mullins, D.A. Paolella, S. Polasky, N.P. Springer, S.K. Thakrar, J.D. Marshall, and J.D. Hill, 2019: Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6001–6006. https://doi.org/10.1073/pnas.1818859116

240. Routledge, P., A. Cumbers, and K.D. Derickson, 2018: States of just transition: Realising climate justice through and against the state. *Geoforum*, **88**, 78–86. https://doi.org/10.1016/j.geoforum.2017.11.015

241. Bullard, R.D., 1996: Environmental justice: It's more than waste facility siting. *Social Science Quarterly*, **77** (3), 493–499. http://www.jstor.org/stable/42863495

242. Bullard, R.D., 2001: Environmental justice in the 21st century: Race still matters. *Phylon*, **49** (3/4), 151–171. https://doi.org/10.2307/3132626

243. Cousins, J.J. and D.T. Hill, 2021: Green infrastructure, stormwater, and the financialization of municipal environmental governance. *Journal of Environmental Policy & Planning*, **23** (5), 581–598. https://doi.org/10.1080/1523908x.2021.1893164

244. Jennings, V., C. Johnson Gaither, and R.S. Gragg, 2012: Promoting environmental justice through urban green space access: A synopsis. *Environmental Justice*, **5** (1), 1–7. https://doi.org/10.1089/env.2011.0007

245. Heckert, M. and C.D. Rosan, 2016: Developing a green infrastructure equity index to promote equity planning. *Urban Forestry & Urban Greening*, **19**, 263–270. https://doi.org/10.1016/j.ufug.2015.12.011

246. Zuniga-Teran, A.A., A.K. Gerlak, A.D. Elder, and A. Tam, 2021: The unjust distribution of urban green infrastructure is just the tip of the iceberg: A systematic review of place-based studies. *Environmental Science & Policy*, **126**, 234–245. https://doi.org/10.1016/j.envsci.2021.10.001

247. Hendricks, M.D. and S. Van Zandt, 2021: Unequal protection revisited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. *Environmental Justice*, **14** (2), 87–97. https://doi.org/10.1089/env.2020.0054

248. Colorado Department of Labor and Employment, 2020: Colorado Just Transition Action Plan. Colorado Department of Labor and Employment, 20 pp. https://cdle.colorado.gov/sites/cdle/files/documents/Colorado%20Just%20Transition%20Action%20Plan.pdf

249. California Office of the Governor, 2020: Executive Order N-79-20: Governor Newsom's Zero-Emission by 2035. State of California, Executive Department. https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-eo-n-79-20-climate.pdf

250. Executive Office of the President, 2021: Executive Order 14008: Tackling the climate crisis at home and abroad. *Federal Register*, **86** (19), 7619–7633. https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad

251. Civil Rights Act of 1964. H.R.7152, 88th Congress, Pub. L. No. 88-352, 78 Stat. 241–268, July 2, 1964. https://www.govinfo.gov/app/details/STATUTE-78/STATUTE-78-Pg241

252. Rehabilitation Act of 1973. H.R. 8070, U.S. Congress, Pub. L. No. 93–112, 87 Stat. 355–393, September 26, 1973. https://www.govinfo.gov/link/statute/87/355

253. Robert T. Stafford Disaster Relief and Emergency Assistance Act. H.R.2707, 100th Congress, Pub. L. No. 100-707, November 23, 1988. https://www.congress.gov/bill/100th-congress/house-bill/2707

254. Watkinson-Schutten, M., 2022: Decolonizing climate adaptation by reacquiring fractionated tribal lands. In: *The Oxford Handbook of Indigenous Sociology*. Walter, M., T. Kukutai, A.A. Gonzales, and R. Henry, Eds. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780197528778.013.42

255. Rosa, E. and T. Dietz, 2012: Human drivers of national greenhouse-gas emissions. *Nature Climate Change*, **2**, 581–586. https://doi.org/10.1038/nclimate1506

256. Rosa, E.A., T.K. Rudel, R. York, A.K. Jorgenson, and T. Dietz, 2015: Ch. 2. The human (anthropogenic) driving forces of global climate change. In: *Climate Change and Society: Sociological Perspectives*. Oxford University Press, 32–60. https://doi.org/10.1093/acprof:oso/9780199356102.003.0002

257. Galli-Robertson, A. and M. Collins, 2019: Super emitters in the United States coal-fired electric utility industry: Comparing disproportionate emissions across facilities and parent companies. *Environmental Sociology*, **5** (1), 70–81. https://doi.org/10.1080/23251042.2018.1495045

258. Pulver, S. and B. Manski, 2021: Corporations and the environment. In: *Handbook of Environmental Sociology*. Schaefer Caniglia, B., A. Jorgenson, S.A. Malin, L. Peek, D.N. Pellow, and X. Huang, Eds. Springer, Cham, Switzerland, 89–114. https://doi.org/10.1007/978-3-030-77712-8_6

259. Marquart-Pyatt, S.T., A.K. Jorgenson, and L.C. Hamilton, 2015: Ch. 12. Methodological approaches for sociological research on climate change. In: *Climate Change and Society: Sociological Perspectives*. Oxford University Press, 369–411. https://doi.org/10.1093/acprof:oso/9780199356102.003.0012

260. Freudenburg, W.R., R. Gramling, S. Laska, and K.T. Erikson, 2008: Organizing hazards, engineering disasters? Improving the recognition of political-economic factors in the creation of disasters. *Social Forces*, **87** (2), 1015–1038. https://doi.org/10.1353/sof.0.0126

261. Rothstein, R., 2017: *The Color of Law: A Forgotten History of How Our Government Segregated America*. Liveright, 368 pp. https://wwnorton.com/books/the-color-of-law/

262. Tierney, K., 2010: Growth machine politics and the social production of risk. *Contemporary Sociology*, **39** (6), 660–663. https://doi.org/10.1177/0094306110386715b

263. Jerolleman, A., 2019: *Disaster Recovery Through the Lens of Justice*. Palgrave Pivot, Cham, Switzerland, 108 pp. https://doi.org/10.1007/978-3-030-04795-5

264. Pelling, M., 2003: *The Vulnerability of Cities: Natural Disasters and Social Resilience*. Routledge, London, UK, 224 pp. https://doi.org/10.4324/9781849773379

265. Platt, R.H., 1999: *Disasters and Democracy: The Politics of Extreme Natural Events*. Island Press, 344 pp. https://islandpress.org/books/disasters-and-democracy

266. Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372** (6549), 8054. https://doi.org/10.1126/science.abc8054

267. Huitema, D., W.N. Adger, F. Berkhout, E. Massey, D. Mazmanian, S. Munaretto, R. Plummer, and C.C.J.A.M. Termeer, 2016: The governance of adaptation: Choices, reasons, and effects. Introduction to the Special Feature. *Ecology and Society*, **21** (3), 37. https://doi.org/10.5751/es-08797-210337

268. York, R., L. Adua, and B. Clark, 2022: The rebound effect and the challenge of moving beyond fossil fuels: A review of empirical and theoretical research. *WIREs Climate Change*, **13** (4), e782. https://doi.org/10.1002/wcc.782

269. Sand-Fleischman, M.G. 2019: Circumventing the Next Trail of Tears: Re-Approaching Planning and Policy for the Climatologically Displaced Indigenous Communities of Coastal Louisiana. Doctor of Philosophy in City and Regional Planning, Cornell University, 387 pp. https://doi.org/10.7298/vfsz-2103

270. Hooks, J.P. and T.B. Miller, 2006: The continuing Storm: How disaster recovery excludes those most in need. *California Western Law Review*, **43** (1), 4. https://scholarlycommons.law.cwsl.edu/cwlr/vol43/iss1/4

271. Laska, S., P. Jenkins, R. Montjoy, M. Farris, M. Gremillion, J. Devalcourt, K.C. King, B. Nowell, and T. Birkland, 2010: Achieving Successful Long-Term Recovery and Safety from a Catastrophe: The Federal Role. CHART Publications, Paper 1. University of New Orleans, Center for Hazards Assessment, Response and Technology. https://scholarworks.uno.edu/chart_pubs/1

272. Ford, J., M. Maillet, V. Pouliot, T. Meredith, A. Cavanaugh, S. Lwasa, A. Llanos, L. Berrang-Ford, C. Carcamo, D.B. Namanya, S. Harper, and I.R. Team, 2016: Adaptation and Indigenous peoples in the United Nations Framework Convention on Climate Change. *Climatic Change*, **139** (3), 429–443. https://doi.org/10.1007/s10584-016-1820-0

273. Moser, S.C., 2016: Reflections on climate change communication research and practice in the second decade of the 21st century: What more is there to say? *Wiley Interdisciplinary Reviews: Climate Change*, **7** (3), 345–369. https://doi.org/10.1002/wcc.403

274. National Academies of Sciences, Engineering, and Medicine, 2016: *Characterizing Risk in Climate Change Assessments: Proceedings of a Workshop*. The National Academies Press, Washington, DC, 100 pp. https://doi.org/10.17226/23569

275. Chapman, D., B. Lickel, and E.M. Markowitz, 2017: Reassessing emotion in climate change communication. *Nature Climate Change*, **7**, 850–852. https://doi.org/10.1038/s41558-017-0021-9

276. Peek, L., H. Champeau, J. Austin, M. Mathews, and H. Wu, 2020: What methods do social scientists use to study disasters? An analysis of the social science extreme events research network. *American Behavioral Scientist*, **64** (8), 1066–1094. https://doi.org/10.1177/0002764220938105

277. Phillips, B.D., 2014: *Qualitative Disaster Research*. Oxford University Press, 192 pp. https://global.oup.com/academic/product/qualitative-disaster-research-9780199796175

278. Beine, M. and L. Jeusette, 2021: A meta-analysis of the literature on climate change and migration. *Journal of Demographic Economics*, **87** (3), 293–344. https://doi.org/10.1017/dem.2019.22

279. Cattaneo, C., M. Beine, C.J. Fröhlich, D. Kniveton, I. Martinez-Zarzoso, M. Mastrorillo, K. Millock, E. Piguet, and B. Schraven, 2019: Human migration in the era of climate change. *Review of Environmental Economics and Policy*, **13** (2), 189–206. https://doi.org/10.1093/reep/rez008

280. Hoffmann, R., B. Šedová, and K. Vinke, 2021: Improving the evidence base: A methodological review of the quantitative climate migration literature. *Global Environmental Change*, **71**, 102367. https://doi.org/10.1016/j.gloenvcha.2021.102367

281. Kaczan, D.J. and J. Orgill-Meyer, 2020: The impact of climate change on migration: a synthesis of recent empirical insights. *Climatic Change*, **158** (3), 281–300. https://doi.org/10.1007/s10584-019-02560-0

282. Piguet, E., R. Kaenzig, and J. Guélat, 2018: The uneven geography of research on "environmental migration". *Population and Environment*, **39** (4), 357–383. https://doi.org/10.1007/s11111-018-0296-4

283. Corburn, J., 2003: Bringing local knowledge into environmental decision making: Improving urban planning for communities at risk. *Journal of Planning Education and Research*, **22** (4), 420–433. https://doi.org/10.1177/0739456x03022004008

284. Rigolon, A. and J. Németh, 2018: "We're not in the business of housing:" Environmental gentrification and the nonprofitization of green infrastructure projects. *Cities*, **81**, 71–80. https://doi.org/10.1016/j.cities.2018.03.016

285. Riahi, K., D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J.C. Cuaresma, S. Kc, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J.C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, and M. Tavoni, 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

286. Rigaud, K.K., A. de Sherbinin, B. Jones, J. Bergmann, V. Clement, K. Ober, J. Schewe, S. Adamo, B. McCusker, S. Heuser, and A. Midgley, 2018: Groundswell: Preparing for Internal Climate Migration. The World Bank, Washington, DC. http://hdl.handle.net/10986/29461

287. Clement, V., K.K. Rigaud, A. de Sherbinin, B. Jones, S. Adamo, J. Schewe, N. Sadiq, and E. Shabahat, 2021: Groundswell Part 2: Acting on Internal Climate Migration. The World Bank, Washington, DC. http://hdl.handle.net/10986/36248

288. Ayeb-Karlsson, S., C.D. Smith, and D. Kniveton, 2018: A discursive review of the textual use of 'trapped' in environmental migration studies: The conceptual birth and troubled teenage years of trapped populations. *Ambio*, **47** (5), 557–573. https://doi.org/10.1007/s13280-017-1007-6

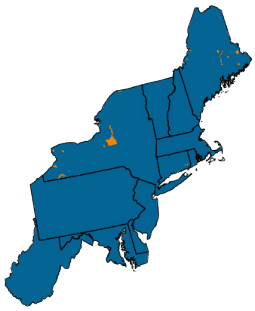
289. Adams, H., 2016: Why populations persist: Mobility, place attachment and climate change. *Population and Environment*, **37** (4), 429–448. https://doi.org/10.1007/s11111-015-0246-3

290. Zander, K.K., S.T. Garnett, H. Sterly, S. Ayeb-Karlsson, B. Šedová, H. Lotze-Campen, C. Richerzhagen, and H.S. Baggen, 2022: Topic modelling exposes disciplinary divergence in research on the nexus between human mobility and the environment. *Humanities and Social Sciences Communications*, **9** (1), 34. https://doi.org/10.1057/s41599-022-01038-2

291. Federal Emergency Management Agency, 2022: Agency information collection activities: Proposed collection; comment request; generic clearance for civil rights and equity. *Federal Register*, **87** (16), 3836–3837. https://www.govinfo.gov/content/pkg/FR-2022-01-25/pdf/2022-01314.pdf

Fifth National Climate Assessment: Chapter 21

# Northeast



# Chapter 21. Northeast

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# Introduction

The Northeast landscape varies from the rural New England coast to the urbanized corridor from Boston to the Mid-Atlantic and inland to the heavily forested Appalachian Mountains. New York, Pennsylvania, Maryland, Delaware, West Virginia, and the District of Columbia all contain parts of the Chesapeake Bay Estuary, the largest estuary in the United States. The Northeast is the homeland of Indigenous Peoples, including 18 Federally Recognized Tribal Nations and many Indigenous Peoples both within the region and who were removed from their lands in the Northeast and relocated to other regions of the United States. Much of the region's employment is in the professional sectors, but jobs related to the natural environment and tourism remain culturally and economically important.[1] Heritage industries tied to resources and agriculture still shape New England and the Mid-Atlantic, including fishing at the coasts, farming in rural areas of Pennsylvania and Maryland, forestry in northern New England, and mining in West Virginia. Seasonal tourism tied to outdoor recreation is particularly important, with summer tourism in coastal communities, fall tourism driven by changing leaves, and winter tourism based on cold-weather sports. Tourism is also important in the cities year-round, with visitors attracted to historical sites, the arts, and the diverse cultures of large cities such as Boston, New York City, Philadelphia, Baltimore, and Washington, DC.

The population of the Northeast has increased by approximately 4.4% since 2010, totaling more than 67 million people. The Mid-Atlantic states experienced the largest increases, with the District of Columbia increasing by 14.6% and Delaware by 10.2%. Some states with larger rural areas—Maine, Pennsylvania, Vermont, and Connecticut—experienced more modest population growth or remained stable. West Virginia was the only state to lose population, declining by 3.2%.[2,3]

Much of the information about the impacts of climate change on the region presented in the Fourth National Climate Assessment (NCA4) remains true today.[4] Urban residents still face increased exposure to extreme heat events, flooding, and episodes of poor air quality. Likewise, rural areas are still susceptible to droughts and floods that affect agricultural productivity and ecosystem function. These events still pose compounding threats to aging transportation, water, and wastewater infrastructure. The communities most vulnerable to climate risks remain those that are historically overburdened and economically disadvantaged in both rural and urban areas. As extreme events continue to occur frequently, these changes are becoming stressors throughout the region—in rural interiors, urban corridors, and the ecosystems supporting coastal communities.

Many early adopters of both mitigation and adaptation action have been in the Northeast. Hurricane Sandy (2012) drove some of this action through programs like the Rebuild by Design effort, which focused on making projects related to disaster rebuilding more resilient to all hazards.[5] In 2014, thirteen projects that won the National Disaster Resilience Competition were located in the Northeast, and by 2022 these projects were in design and construction phases, with some projects substantially complete.[6,7] Northeast cities and states participated in numerous other efforts, from the Rockefeller Foundation's 100 Resilient Cities program to Massachusetts's landmark integration of climate adaptation into its FEMA State Hazard Mitigation Plan.[8] States, Tribal Nations, and local governments are also beginning to fund both planning and project implementation with non-grant public funding, and private-sector actors are increasingly self-funding their own action. Advancements in adaptation and mitigation efforts in the Northeast provide an opportunity to document progress and identify remaining knowledge gaps that constrain or enable climate action.

In the Northeast, both adaptation and mitigation actions are proceeding, particularly in response to repeated impacts from extreme weather events (KM 21.1). Adaptation is also being documented in the ocean and coastal regions (KM 21.2). Human and ecosystem climate change impacts are disproportionately affecting overburdened communities and people, leading to an increased focus on equity in adaptation and mitigation efforts (KM 21.3). Deliberate action plans for both mitigation and adaptation are being completed throughout the Northeast by states, municipalities, and Tribal Nations (KM 21.4), but the progress of action in both the public and private sector will depend on the ability to fund and finance it (KM 21.5).

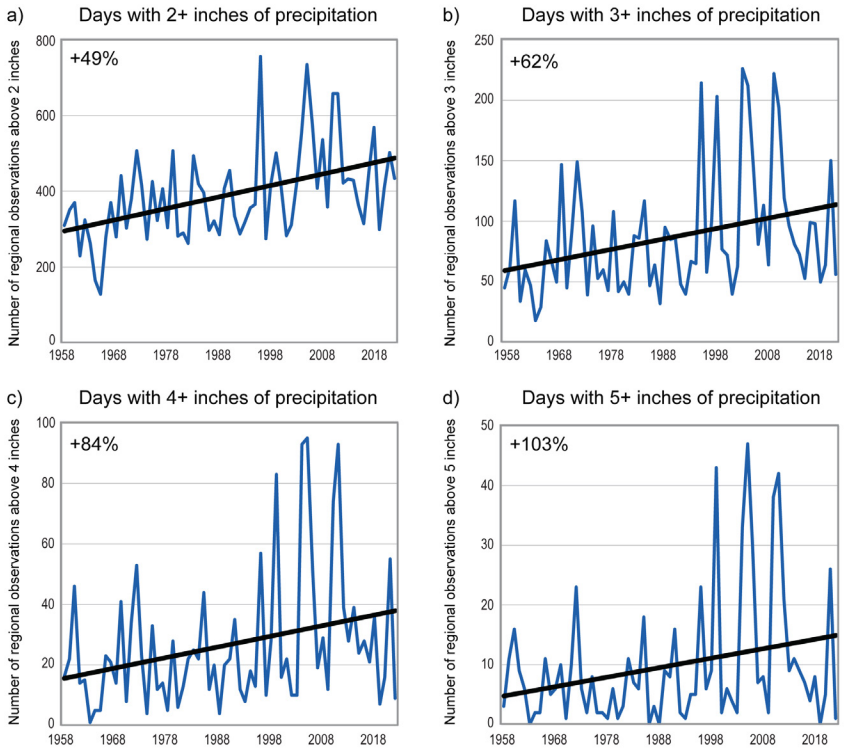
## Key Message 21.1

# Chronic Impacts of Extreme Weather Are Shaping Adaptation and Mitigation Efforts

The Northeast continues to be confronted with extreme weather, most notably extreme precipitation—which has caused problematic flooding across the region—and heatwaves (*very likely*, *high confidence*). In response, climate adaptation and mitigation efforts, including nature-based solutions, have increased across the region (*high confidence*), with a focus on emissions reductions, carbon sequestration, and resilience building (*medium confidence*).

Precipitation in the Northeast has increased in all seasons (Figure 2.4),[292] and extreme precipitation events (defined as events with the top 1% of daily precipitation accumulations) have increased by about 60% in the region—the largest increase in the US (Figure 2.8; see also Figure 21.1). These changes may be due to an increase in tropical systems during the Atlantic hurricane season in September and October, especially at interior locations as far inland as West Virginia.[9,10,11,12] The increase in extreme precipitation and associated flooding could also be due to the higher overall water availability throughout the region.[13]

### Trends in Extreme Precipitation in the Northeast

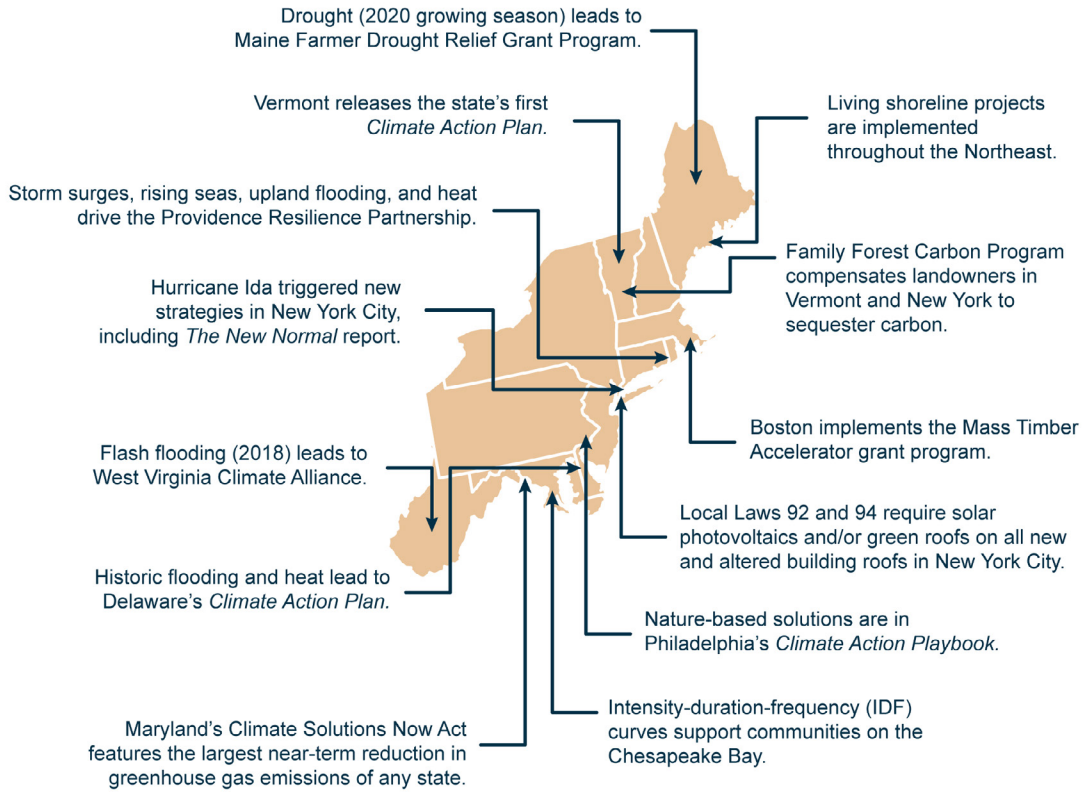



**The number of days in the Northeast with extreme precipitation has increased.**

**Figure 21.1.** The four charts show the number of daily events per year with precipitation totals equal to or exceeding 2, 3, 4, and 5 inches from 1958–2022 (blue lines), along with trend lines (black) computed from linear regressions over the full period. Numbers in the top left corner show the percent increase relative to the long-term average, computed as the difference between the end points of the trend lines divided by the 1958–2022 average. The number of daily events is defined as the total number of extreme precipitation accumulations recorded at all stations across the observing network in the Northeast. See the figure metadata for details on the methodology. The trends shown suggest an increase in the frequency of extreme precipitation, with larger increases for the more extreme precipitation events. Figure credit: USDA Forest Service, Drexel University, NOAA NCEI, and CISESS NC.

Urban and flash flooding is typically triggered by short-duration (e.g., sub-daily, sub-hourly), high-intensity, localized "cloudburst" events, often caused by convective thunderstorms. Although historical and forecasted trends in sub-daily precipitation event attributes and frequencies have not yet been evaluated for the region, the occurrence of these events has already begun to motivate action (Figure 21.2). For example, in 2021 after back-to-back storms (Hurricane Henri followed by Hurricane Ida) shattered records for the greatest one-hour rainfall events and resulted in 13 deaths, the City of New York committed to educate, train, and acclimate residents to the potential impacts of extreme weather, expand flood protection to include both inland and coastal communities, and reimagine its drainage system, among other initiatives.[14]

## Examples of State and Local Responses to Extreme Weather




**Northeastern states and cities have adopted a range of plans, programs, and policies in response to extreme weather, many of which include nature-based strategies.**

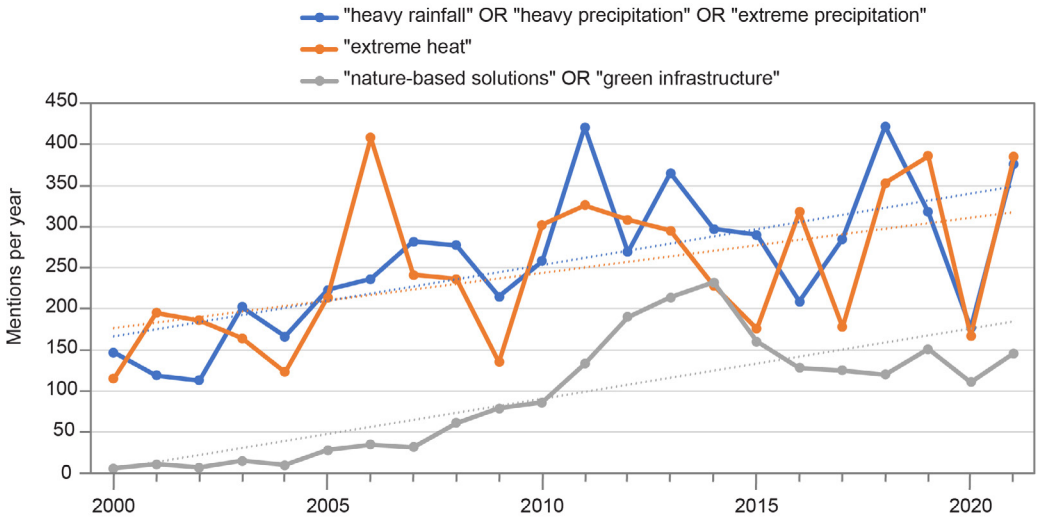
**Figure 21.2.** This map highlights efforts, many of which are nature-based, that address climate change impacts by building resilience or promoting mitigation measures. In some cases, these efforts are specific programs or projects, such as the Family Forest Carbon Program in Vermont and New York. In other cases, local and statewide plans include broader attention on natural and nature-based strategies. Figure credit: Drexel University and USDA Forest Service.

The frequency of droughts in the Northeast decreased between 1901 and 2015, albeit not as much as would have been expected given the region's increase in average precipitation.[15] Although higher overall humidity can reduce the effect of rising temperatures on how quickly water evaporates from crops,[16] farmers[17,18] and other stakeholders report impacts triggered by highly variable soil moisture. For example, thaw events, extended spring conditions, and longer mud seasons have reduced mobility on unpaved roads that are important for rural travel and logging operations.[19]

As in the rest of the country, the region's heatwaves are lasting longer and are more severe, generally increasing heat stress, especially in densely populated areas (KM 2.3). By midcentury, heat index values over 100°F are projected to increase threefold in the Northeast under an intermediate scenario (RCP4.5).[20]

Extreme weather creates a range of social, economic, and ecological impacts in urban, coastal, rural agricultural, and wild landscapes, as demonstrated by an increase in reporting on extreme weather in the Northeast media (Figure 21.3). Social vulnerability to climate stressors is unequally distributed throughout the region. Individuals who are low income, minority, and/or without high school diplomas are, respectively, 35%, 20%, and 20% more likely than individuals who are not members of those groups to live in areas with the highest projected traffic delays due to high tide flooding. Minorities in the region are 16% more likely than non-minorities to experience property damage or loss due to the highest projected inland flooding damages.[21] In New York City, high levels of social vulnerability to climate change are consistently found in neighborhoods with lower incomes and higher shares of African American and Hispanic residents.[22] Ecosystems are also becoming more vulnerable to extreme weather events as climate change increases stressors such as pests that survive in warmer winter nights.[23]

## Northeast US Newspaper Mentions of Extreme Weather and Nature-Based Solutions




**Mentions of extreme weather events and nature-based solutions are increasing across Northeast media.**

**Figure 21.3.** As the Northeast continues to experience extreme weather events, news articles highlight the trend in climate action planning. Natural and nature-based features are a common strategy used in these efforts. Solid lines show mentions related to heavy precipitation (blue), extreme heat (orange), and nature-based solutions and green infrastructure (gray) during 2000–2021, with dotted lines showing the estimated trend line for each category. Figure credit: Drexel University and USDA Forest Service.

Future increases in heatwaves are projected to increase mortality rates in the region's major urban areas (KM 15.1).[24] Among workers who are exposed to weather conditions, minorities are 7% more likely than non-minorities to lose labor hours under 2°C (3.6°F) of global warming.[21] Extreme heat is also putting increased pressure on emergency managers and utility corporations, as well as causing human mortality.[25]

High population density, problematic land-use configurations, industry and other pollution sources, contaminated soils, aging infrastructure, and a legacy of buried and/or heavily modified natural drainage systems exacerbate extreme weather impacts in urban areas (KM 12.2).[26] Even under non-extreme weather conditions, impervious surfaces (e.g., sidewalks, roofs, roadways, compacted lawns) generate large quantities of runoff from precipitation, yielding nonpoint source pollution, streambank erosion, habitat degradation,

downstream flooding, impaired mobility, and reduced access to services. Extreme weather accelerates and amplifies these phenomena. Localized rainfall flooding can damage homes and businesses with below- or at-grade spaces (e.g., basements, ground floors, subways). Hurricane Ida triggered rainfall flooding that killed 11 people in New York City who could not escape below-grade dwellings[27] and inundated below-grade sections of Philadelphia's Vine Street Expressway. In Baltimore, flooding interrupts basic services, including access to food distribution centers, schools, childcare facilities, health services (e.g., dialysis or methadone clinics); in addition, the city's elderly, poor, mentally ill, mobility-constrained, and those with limited experience of flooding were identified as the most susceptible to flooding effects.[28] More broadly across Maryland, probabilistic flood mapping and recent flood events indicate that flood risks extend beyond the 100-year floodplain in some places, particularly in urban watersheds.[29]

Increased precipitation can also impact less intensively developed areas and along the coasts. Observed and projected increases in precipitation in the Susquehanna River basin, which contributes about half of all freshwater discharges into the Chesapeake Bay, are drivers for flood risk, poor water quality, and changes to habitats in the bay.[30,31] Wetter springs are expected to continue to delay planting, postpone harvests, and reduce crop yields.[23]

Stronger storm surges during tropical systems and nor'easters increase the risk of coastal flooding, also exacerbated by sea level rise.[32,33] Flood hazards for coastal cities are projected to increase in frequency and magnitude in the coming decades in the absence of near-term adaptive measures.[34] In August 2020, Tropical Storm Isaias flooded the Eastwick neighborhood of southwest Philadelphia. This overburdened community is home to one of the largest Superfund sites in the country and also faces coastal and compound flood risks due to sea level rise from the Delaware River.

Governmental and nongovernmental groups are mapping hazards to assist in responding to extreme events. New York City and Boston developed detailed maps of the portions of each city that are at risk of rainfall-induced inland flooding under coincident tidal conditions and sea level rise. Maps of croplands and forests most vulnerable to saltwater intrusion are also being developed.[35] Heat vulnerability maps have been developed for cities (e.g., Philadelphia), counties (e.g., Essex County, New York), and states (e.g., Vermont) throughout the region. Such maps can assist with identifying at-risk communities. Heat risk-reduction strategies tend to emphasize direct assistance to at-risk residents and impacts on energy utilities. Chelsea, Massachusetts, and New York City have distributed air conditioners to reduce the impacts of extreme heat, and Philadelphia recently released a Beat the Heat Toolkit.

States, regional planning commissions, Tribal Nations, and localities are also responding by incorporating climate resilience into FEMA hazard mitigation plans (HMPs; KM 31.4). Many action plans are developed through collaborative public–private processes. Atlantic County, New Jersey, has initiated a Regional Resilience and Adaptation Action Plan through a partnership between the New Jersey Bureau of Climate Resilience Planning and various regional stakeholder groups. The Stafford Act[36] requires that states and Tribes submit approved HMPs to FEMA every five years to be eligible for nonemergency Stafford Act disaster assistance and FEMA hazard mitigation grants. The act also requires each state to establish a process to support development of local HMPs. Climate-resilient HMPs incorporate downscaled climate projections, resident experiences, and local visions. Increasingly, HMPs directly address the goals of other plans developed at the local, regional, Tribal, or state level, including sustainability plans and comprehensive plans (e.g., Nashua, New Hampshire; Springfield and Boston, Massachusetts; Shinnecock Nation; and New York City). In most cases, these efforts are in the planning phase, but some early-adopter locations are beginning to implement their resilience projects. Local and state FEMA hazard mitigation planning guides now encourage climate-informed planning and projects that incorporate resilience.[37,38]

With increased awareness of extreme weather impacts, climate action plans and projects in the Northeast are utilizing natural and nature-based features (NNBFs) more frequently (Figure 21.2). NNBFs restore landscape resilience to disturbances, protect downstream water bodies, and deliver a range of co-benefits that protect public health, reduce flood damage, improve water and air quality, and control ambient air temperatures (KM 9.3). NNBFs utilize plant or soil systems for environmental, economic, and social benefits.[39] Several recent studies focused in New Jersey, New York, and Connecticut emphasize the role of NNBFs in buffering coastal flood losses,[40,41] detaining and retaining runoff,[42,43] reducing combined sewer overflows,[44] alleviating heat impacts,[45,46] and introducing vegetation that is resilient to future floods and droughts.[47] Changes in precipitation can also reduce the stormwater capture performance of NNBFs,[42,48,49] and the adaptation value of NNBFs can depend heavily on unique local conditions.[50] Several Tribal NNBFs are also in place across the Northeast (KM 16.3). For example, the Shinnecock Nation has developed a kelp aquaculture farm and a living shoreline featuring oyster reefs on Long Island, New York.[51] In partnership with the Town of Mashpee, Massachusetts, the Mashpee Wampanoag Tribe also built an oyster reef.[52] The Wampanoag Tribe of Gay Head (Aquinnah), Massachusetts, rebuilt and replanted beach dunes for coastal protection.[53]

Climate mitigation is also a target for NNBFs, including carbon sequestration and greenhouse gas (GHG) emissions reductions.[54,55,56] Local, Tribal, and state planners are moving toward multi-objective approaches when incorporating NNBFs as part of the toolbox for climate adaptation and mitigation, with increasing focus on equitable climate outcomes where co-benefits are needed for heat, flooding, and well-being (Figure 21.2).

## Key Message 21.2

## Ocean and Coastal Impacts Are Driving Adaptation to Climate Change

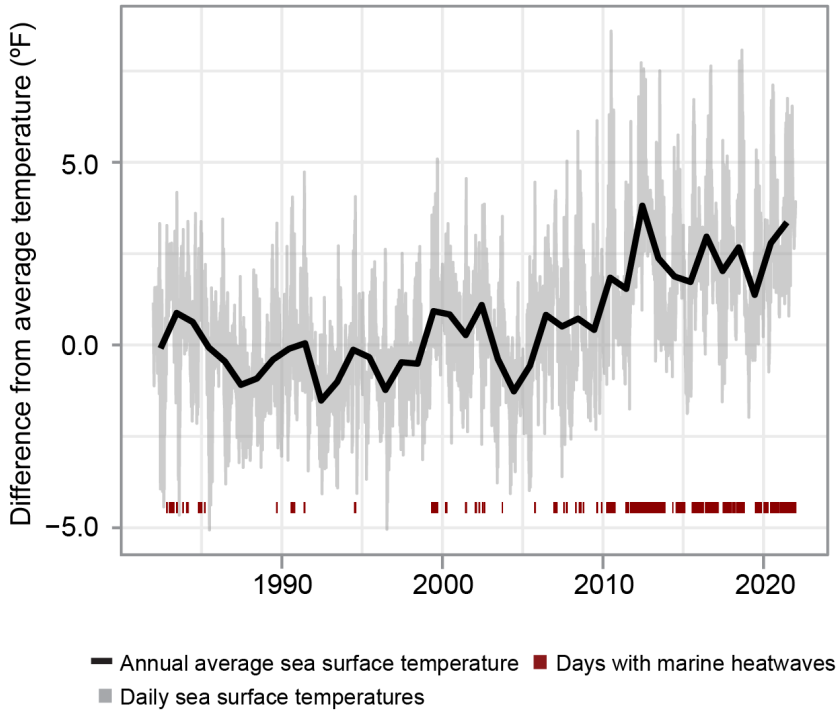
The ocean and coastal habitats in the Northeast are experiencing changes that are unprecedented in recorded history, including ocean warming, marine heatwaves, sea level rise, and ocean acidification (*high confidence*). Changing ocean conditions are causing significant shifts in the distribution, productivity, and seasonal timing of life-cycle events of living marine resources in the Northeast (*high confidence*). These impacts have spurred adaptation efforts such as coastal wetland restoration and changes in fishing behavior (*high confidence*).

Ocean warming, more frequent and intense marine heatwaves, sea level rise, and ocean acidification are harming aquatic ecosystems and ecosystem services, and these impacts are expected to be exacerbated by future climate change (KMs 2.1, 3.4, 9.1, 9.2, 10.1; App. 4.4).[57,58,59,60] Climate-driven shifts in distribution, productivity, and phenology (seasonal timing of life-cycle events) are increasing in prevalence and magnitude across species, from phytoplankton to whales.[59,61]

Ocean temperatures in the continental shelf bottom waters of the Northeast have increased by as much as 0.15°F to 0.7°F per decade (Friedland et al. 2020) due to changes in atmospheric circulation from a persisting positive North Atlantic Oscillation (NAO; a large-scale climatic phenomenon) and a weaker Atlantic Meridional Overturning Circulation.[62] The northward shift of the Gulf Stream increased the salinity and temperature of subsurface waters on the Northwest Atlantic shelf.[63] Several notable marine heatwaves affected the Northwest Atlantic over the last decade (Figure 21.4),[63,64,65] associated with Gulf Stream variability, atmospheric jet stream motions, and the increased presence of masses of warm water formed from the Gulf Stream called warm core rings.[66] Changes in ocean temperature and circulation have also decreased the extent, temperature, and duration of the cold pool, a near-bottom coldwater feature in the Mid-Atlantic and an important habitat for fish productivity.[58,67]

These changes are impacting productivity at the base of the region's ocean ecosystem and changing the composition of the phytoplankton community.[68] The overall diversity and abundance of the zooplankton community has increased,[68] but the biomass of key zooplankton species has declined.[59,69] These changes can restructure communities and have cascading effects throughout the food web. For example, the negative impact of warming on the copepod *Calanus* has been linked to shifts in the distribution of right whales along the Northeast shelf.[70,71]

## Ocean Temperatures and Marine Heatwaves

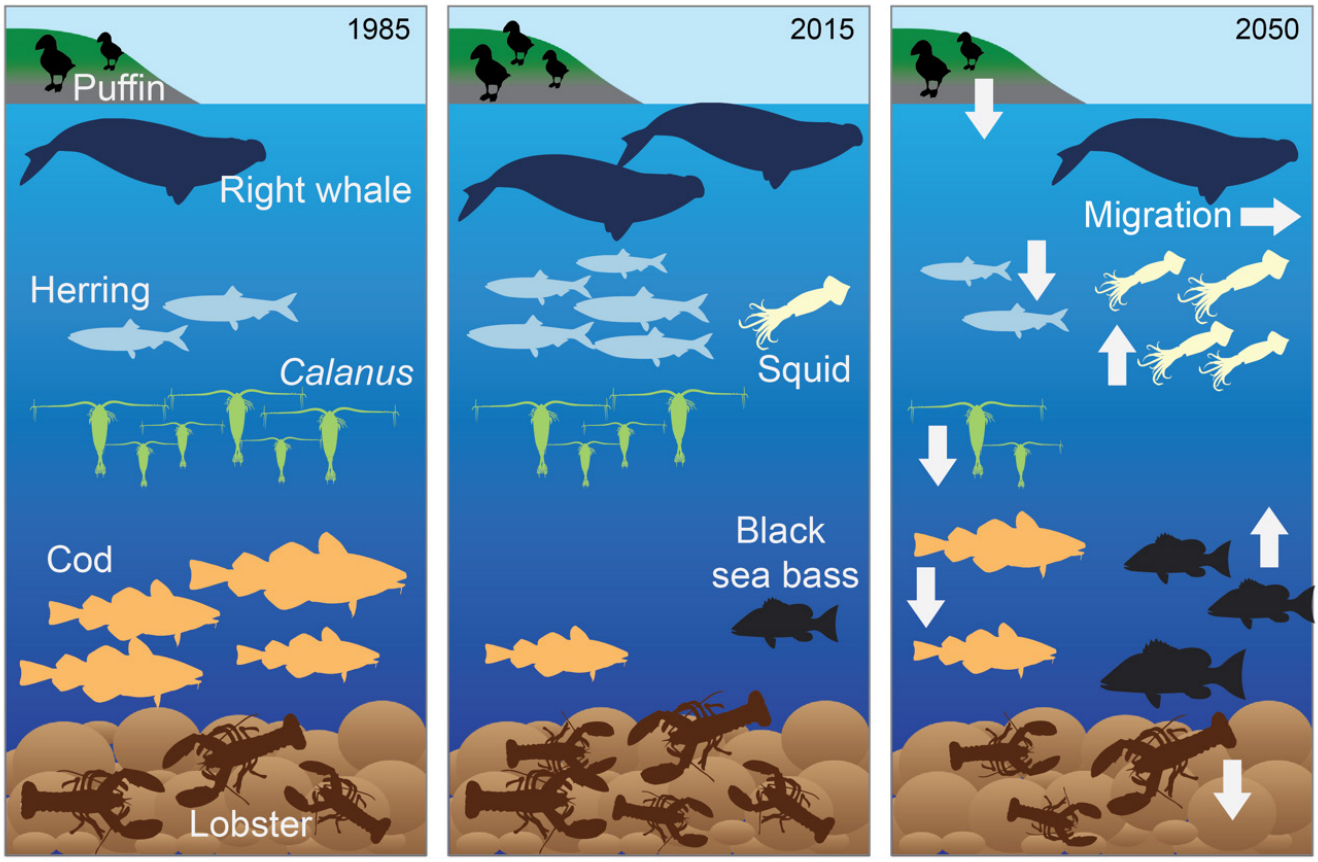



**Oceans are growing warmer and marine heatwaves are more frequent, which is impacting marine ecosystems in the Northeast.**

**Figure 21.4.** Annual average sea surface temperature (SST) anomalies (solid black line) and daily SST anomalies (light gray line) for the Gulf of Maine (region defined as ecological production unit, an ecologically distinct ecosystem). Differences from the long-term average are estimated using a 30-year climatology reference period of 1982–2011. Days meeting marine heatwave criteria are noted (red tick marks). Marine heatwave status was determined following the methods of Hobday et al. (2016).[72] The figure shows continued warming of the Gulf of Maine, with 2022 among the warmest years on record. In addition to the warming trend, the periodicity of extreme temperature events (i.e., marine heatwaves) has increased in the region. Adapted from Gulf of Maine Research Institute 2022.[73]

Fish stocks are shifting northeastward along the shelf and into deeper waters.[58] Traditional Mid-Atlantic fish species (e.g., black sea bass)[74,75] are increasing, and subarctic species (e.g., northern shrimp and Atlantic cod)[59] face declines in the Gulf of Maine (Figure 21.5). Warming is changing the distribution of bottom-dwelling species, including American lobster, Atlantic surf clams, and sea scallops (Figure 21.6).[76,77] New research directions focus on the impacts these changes have on early life stages for key species like Atlantic mackerel.[78]

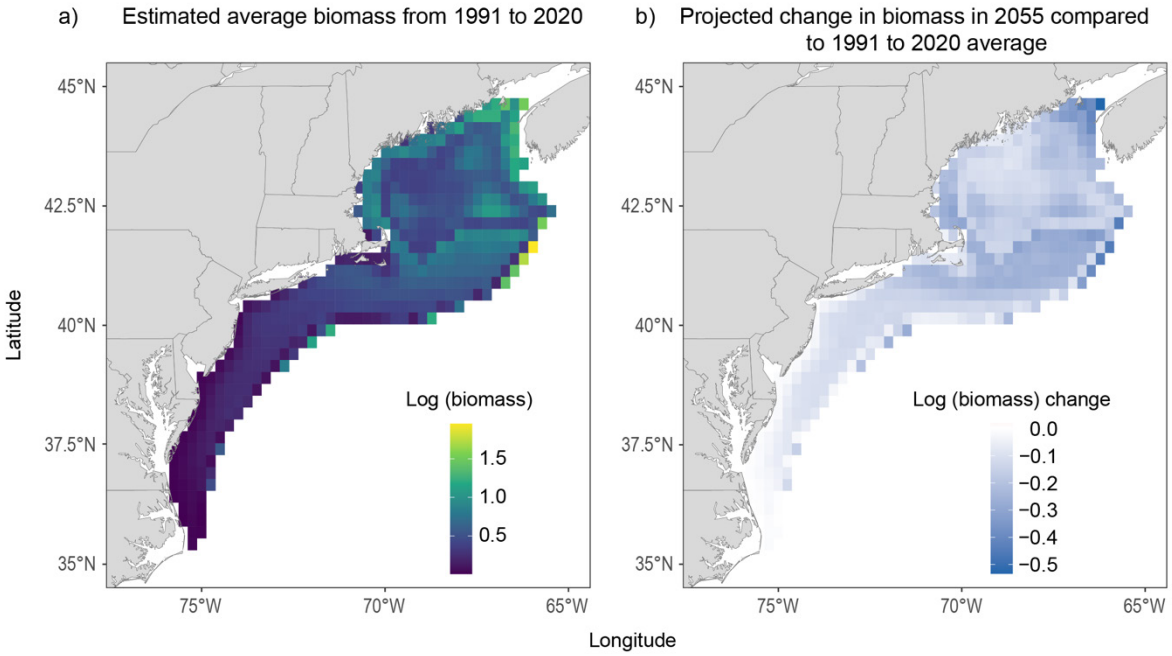
## Past (1985), Present (2015), and Future (2050) of the Gulf of Maine Ecosystem




**Shifts in the abundance and composition of species in the Gulf of Maine are expected to continue with additional warming.**

**Figure 21.5.** In 1985, conditions in the Gulf of Maine ecosystem were cool, and subpolar species (puffin, right whales, and Atlantic herring) were not abundant due to human activities and natural variability. By 2015, Atlantic cod abundance was low due to overfishing and rising temperatures, whereas temperate species (e.g., black sea bass and squid) became prevalent due to warming. Under an intermediate scenario (RCP4.5), by 2050 many subpolar species (e.g., lobster, Atlantic cod, Atlantic herring, and *Calanus*, a copepod) are expected to decline (down arrows), and temperate species will increase (upward arrows). With better management, Atlantic cod abundance will tend to increase, but it will be counteracted by decreased productivity due to warming. Right whales will increase with better management but are expected to move out of the Gulf of Maine (horizontal arrow) due to the impacts of warming on the distribution and abundance of their prey. Local fishing communities will need to shift effort to harvest species that have become more abundant. Adapted from Pershing et al. 2021[59] [CC BY 4.0].

## Changing Distribution of Fishery Resources in the Northwest Atlantic Ocean




**The distribution and abundance of American lobster are expected to decrease by midcentury.**

**Figure 21.6.** The figure shows (**a**) predicted changes in American lobster (*Homarus americanus*) distribution and abundance based on the estimated baseline biomass (log-transformed scale) from 1991 to 2020 (the color scale ranges from yellow [high biomass] to purple [low biomass]) and (**b**) future projected change in biomass in 2055 compared to the baseline period (the color scale ranges from no change [white] to a decrease in biomass [darker blue]). Projections suggest a decrease in the future biomass of lobster due to ocean warming. Adapted from Allyn et al. 2020[79] [CC0 1.0].

The timing of important life-history events, such as fish feeding and spawning migrations, is shifting in the Northeast. Spring and autumn phytoplankton blooms occurred later in recent decades.[80] Larval fish occurrence and fish migration are both happening earlier.[81,82,83] Warmwater fish remain longer in Rhode Island's Narragansett Bay, while coldwater species stay for shorter periods,[84] changing when species can be fished. Warming seas are linked to increased cold-stunning events for Kemp's ridley sea turtles in the northwest Atlantic, in which turtles acclimated to warm water become motionless when subjected to sudden cold water.[85]

Increased temperatures make some diseases more prevalent in aquatic organisms, affecting the availability of seafood and increasing seafood-borne diseases. Shell disease in American lobster is associated with changing molting patterns due to spring warming and increased exposure to summer heat.[86] Climate change is expected to cause higher mortality of blue crabs due to infection by *Hematodinium*[87] and *Callinectes sapidus* reovirus 1.[88] Harmful algal blooms occur more often in the Northeast.[89] Evidence links climate change to an increase in the potential growth rates and bloom-season duration of *Margalefidinium polykrikoides*, which kills finfish and bivalve mollusks,[89,90,91] and in the number of blooms of *Prorocentrum minimum*.[92,93] Increasing temperature is linked to increases in the occurrence of pathogens (e.g., *Vibrio* species),[60] which are among the most important causes of seafood-borne diseases.[94]

Increasing water temperature is expected to alter fish and shellfish community structure in estuaries.[95] Significant declines in the relative habitat usage of several economically important finfish species (e.g., Atlantic croaker, spot, and summer flounder) were observed in the Chesapeake Bay from 2008 to 2019,[96] driven in part by the NAO.

The abundance of subtropical species such as pinfish and white shrimp is expected to increase in the Chesapeake Bay and coastal lagoons, whereas more temperate species, such as soft clam and sand shrimp, might decrease.[97,98] In the Chesapeake Bay, an observed increase in the abundance of white shrimp[99] was related to favorable environmental conditions, including rising temperatures. Projections of shorter winter periods and warmer winter temperatures in the Chesapeake Bay suggest that by 2100, blue crabs will grow faster and improve their overwinter survival, increasing the productivity of the population.[100]

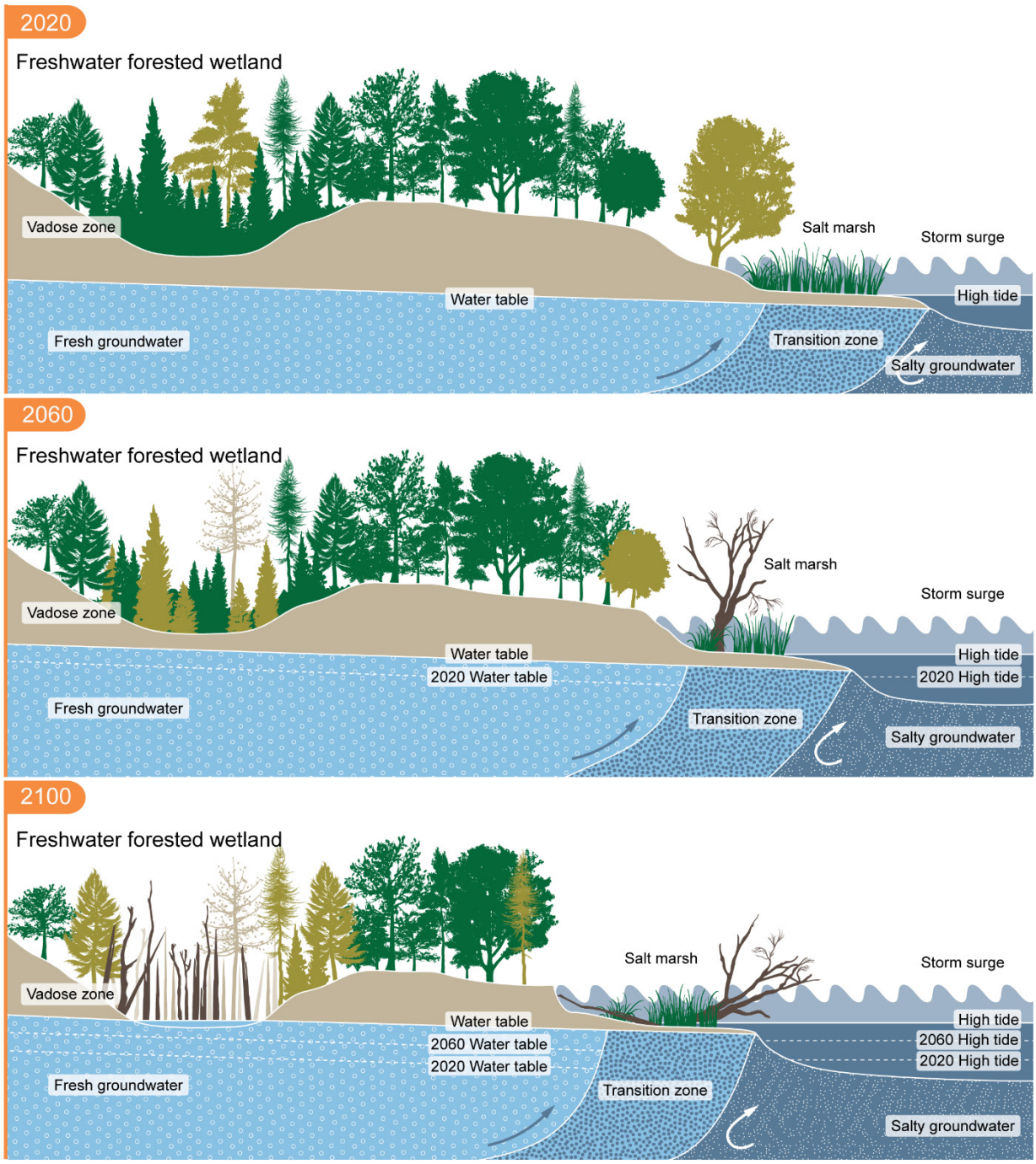
Combined with changes in salinity, ocean acidification exerts stress on shell-building organisms in the region (KM 2.3). The Mid-Atlantic Bight is acidifying faster than other Atlantic coastal regions and the open ocean.[101] Ocean acidification may impact fishery resources, including American lobster, scallops, oysters, clams, and mussels.[102] For example, projections of sea scallop biomass suggest a potential decrease of more than 50% by the end of the century under a very high scenario (RCP8.5) and 13% under an intermediate scenario (RCP4.5).[103] Scallops are one of the most lucrative fisheries in the Northeast, and acidification will have socioeconomic ramifications.

Oxygen loss in ocean and coastal areas, which is correlated with water temperature and nutrient enrichment, is also an important driver of marine ecosystem change (KM 2.3). The rate of change varies by region, with coastal waters of the Northeast showing a drop in oxygenation that outpaces that of the global ocean and broader North Atlantic.[104,105,106] Projected increases in precipitation discussed in Key Message 21.1 will lead to increased runoff and nutrient loading into coastal waters. Estuaries such as the Chesapeake Bay that receive significant amounts of nutrients from the watershed that stimulate algae production experience low oxygen levels (hypoxia),[107] especially during the summer months. Furthermore, temperatures are rising in the region, and in the Chesapeake Bay this is driven by increases in air temperature and in reflected longwave radiation, as well as by warming of the continental shelf.[108] Marine heatwaves are also increasing in frequency, number of days per year, and yearly cumulative intensity in the Chesapeake Bay, which is projected to reach a semipermanent marine heatwave state by 2100, relative to present day.[109] Under such a condition, extreme temperatures will occur for more than six months in a year. Increases in the temperature and intensity of marine heatwaves are expected to decrease the dissolved oxygen content of water and worsen the hypoxic conditions, with consequent negative effects on fish, shellfish, and other living organisms.[110,111]

Sea level rise, tropical and extratropical cyclones, storm surges, and flooding are changing natural coastal wetlands and forests and the species that inhabit them (Figure 21.7; Ch. 9).[112] Impacts of rainfall and riverine floods on coastal areas include shoreline erosion,[113] damage to infrastructure and agriculture, and the degradation and loss of coastal ecosystems, including tidal wetlands and forests (KMs 9.1, 9.2).[114,115] Coastal inundation poses increased risks to aquifers and buried structures, such as septic tanks and pipes, which would degrade water quality.[116] Coastal zone groundwater supplies (such as in Long Island, New York, and Cape May County, New Jersey) are also vulnerable to saltwater intrusion from sea level rise.[117,118]

Coastal forests in the Northeast, such as the Lower Eastern Shore of Maryland and other areas of the Delmarva Peninsula, have been affected by saltwater intrusion and salinization of the soils.[119,120] When coastal forests are invaded by salt water, they transform into tidal marshes, leaving behind standing dead trees, called ghost forests,[121,122] and promoting the growth of *Phragmites australis*, an invasive reed grass that provides less suitable habitats for fishes, crustaceans, and other invertebrates.[123]

## Projected Changes in Coastal Forests




**Rising sea levels kill trees and transform coastal forests into marshes, damaging vital ecosystems and the services they provide to the community.**

**Figure 21.7.** As sea level rises, the water table also rises; the vadose zone (which is between the ground surface and the groundwater table) becomes thinner, bringing the water table closer to the surface; and tidal flooding and storm surges reach farther inland, resulting in forest dieback and conversion of forested wetlands to standing-water wetlands. Over time, these changes result in permanent habitat shifts. Adapted from Sacatelli et al. 2020.[122]

Advancements in predictive modeling of coastal and marine resources[59,79,124] are informing expectations of future climate-driven changes in the thermal habitat of species, such as American lobster (Figure 21.6) and sea scallops, and enabling marine resource managers to anticipate risks to these fisheries. Projections of habitat changes in the Northeast suggest that sea scallops will undergo a northward shift, while American lobster will move farther offshore over the next 80 years.[125] Information on expected shifts in the distributions of marine resources is important for adaptive actions that can support livelihoods and local economies reliant on these resources.

Adaptation responses to sea level rise and shoreline erosion include the use of natural and nature-based features, such as eco-engineered oyster reefs (e.g., oyster castles), and management and restoration[126,127] of coastal wetlands.[128,129,130] Collaborative learning and exchange of ideas among multidisciplinary groups, including salt marsh professionals, is facilitating salt marsh management and restoration in the region; techniques include using drone technology to monitor living shorelines and constructing and evaluating runnels (shallow, narrow channels used to drain water from the marsh surface at low tide).[131,132,133,134] Other measures are aimed at managing stormwater and reducing carbon dioxide ($CO_2$) emissions to mitigate ocean acidification.[135]

New England and Mid-Atlantic fishing communities are particularly vulnerable to climate impacts and face declining fishing opportunities unless they adapt, either through catching new species or fishing in new locations.[136] Actions undertaken to reduce potential climate change impacts to Northeast fisheries range from individual actions to changes in federal governance.[137] Fishing patterns such as location and timing have altered in response to shifting species distributions (e.g., summer flounder). Effective adaptation strategies include diversifying species targeted for harvest in response to changing availability and improving fleet mobility, so fishers can follow their target species.[138] Marine heatwaves led to an early influx of molted lobsters, prompting the lobster industry to implement changes throughout the supply chain to avoid price drops should another warm year with early and intense landings occur.[139] However, key barriers to adaptation efforts include fisheries specialization and dependency, fishery access, working waterfront and workforce issues, and management system responsiveness.[140] Furthermore, interactions with threatened and endangered aquatic mammals can complicate adaptation efforts. Changes in right whale patterns due to warming have increased concern about the risk of vessel strikes. This has prompted calls for increased fishing gear regulations, with possible ramifications for the lobster industry.[141]

## Key Message 21.3

## Disproportionate Impacts Highlight the Importance of Equitable Policy Choices

Extreme heat, storms, flooding, and other climate-related hazards are causing disproportionate impacts among certain communities in the Northeast, notably including racial and ethnic minorities, people of lower socioeconomic status, and older adults (*very likely*, *very high confidence*). These communities tend to have less access to healthcare, social services, and financial resources and to face higher burdens related to environmental pollution and preexisting health conditions (*very likely*, *high confidence*). Social equity objectives are prominent in many local-level adaptation initiatives, but the amount of progress toward equitable outcomes remains uneven (*very likely*, *high confidence*).

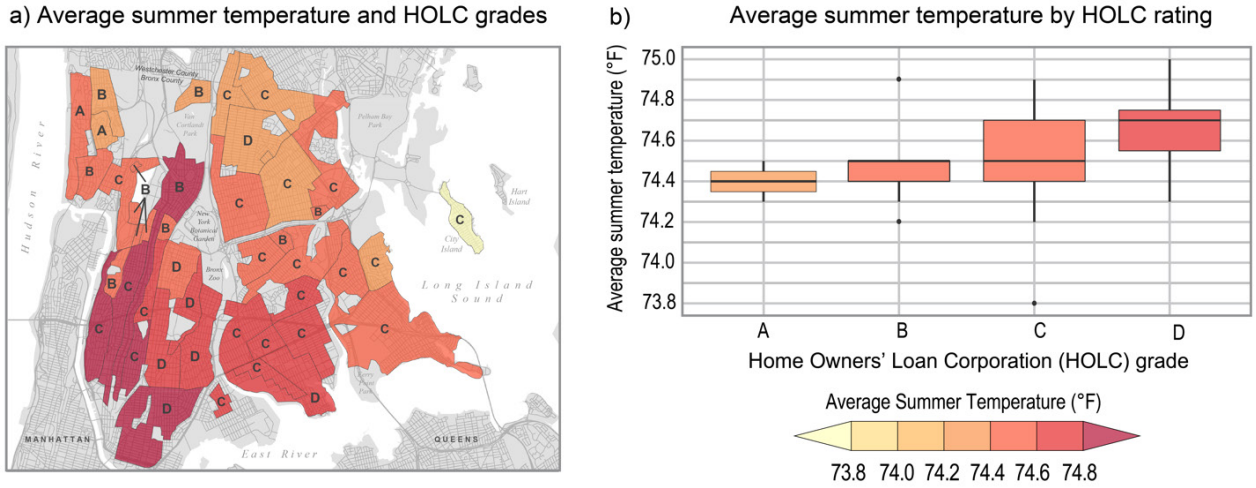
Across the Northeast, the disproportionate impact of climate change and extreme weather on racial and ethnic minorities and low- and moderate-income communities has provided focus to new advocacy and policy work to advance equity and environmental justice.

Climate impacts—including extreme heat, stronger storms, flooding, and pollution—compound the environmental, health, and socioeconomic burdens on some communities (KMs 12.2, 15.2). These burdens include historical racially based injustices such as redlining (a discriminatory practice by which financial products such as loans and insurance were refused or limited in specific geographic areas),[142,143,144,145,146] land dispossession and forced migration of Indigenous Peoples, and disinvestment in poor communities and communities of color. In response, local, Tribal, and state governments are increasingly working directly with community organizations, Indigenous Peoples, and environmental justice groups to develop new approaches to these challenges.

Analyses of summer land surface temperature and sociodemographic data reveal heat exposure disparities across Northeast neighborhoods. Specifically, neighborhoods with higher proportions of racial and ethnic minorities, people of lower socioeconomic status, and households without automobile access experience higher temperatures.[147]

Relative to non-redlined neighborhoods, historically redlined areas in the Northeast show consistent city-scale patterns of elevated land surface temperatures.[148] For instance, Figure 21.8 shows higher average summer temperatures in redlined neighborhoods in the Bronx, New York. People of color tend to live in census tracts with higher surface urban heat island intensity than non-Hispanic Whites, and this difference is particularly pronounced in the Northeast.[149] Across the United States, higher heat is experienced by racial and ethnic minorities in metropolitan statistical areas more segregated from Whites and in census tracts with lower socioeconomic status and higher percentages of Black and Asian residents.[150]

## Summer Temperature Differences by Neighborhood in the Bronx, New York




**Average summer temperatures are generally higher in historically redlined neighborhoods in the Bronx, New York.**

**Figure 21.8.** Historically redlined areas, defined by lower Home Owners' Loan Corporation (HOLC) grades that deprived certain areas of federal loans and insurance, typically show higher temperatures relative to non-redlined neighborhoods, leading to greater likelihood of heat exposure for areas with lower socioeconomic status and higher percentages of racial and ethnic minorities in the Bronx, New York (1981–2010). The letters A, B, C, and D on the figure correspond to the four categories used by the HOLC: "Type A (Best), Type B (Still Desirable), Type C (Declining), and Type D (Hazardous)."[143] Figure credit: Union of Concerned Scientists, RAND Corporation, Columbia University, NOAA NCEI, and CISESS NC.

Compared with the historic territories of Indigenous Peoples, present-day Tribal lands experience nearly two additional extreme heat days per year and a decrease of nearly 23% in annual average precipitation.[151] For some members of Tribal Nations across the Northeastern US, climate change impacts on Tribal reservation or trust lands, which in some Tribal Nations have been reduced to 1 square mile or less, pose serious threats to Tribal cultures. One of the greatest threats will be the shifting of ecosystems and species migration beyond Tribal lands or regions.[152] Loss of access to culturally significant locations harms the physical and mental health of Indigenous Peoples (KM 15.2).[153]

Temperature extremes are related to a larger fraction of cardiorespiratory deaths in the Northeast and industrial Midwest (compared with other regions), particularly in areas with higher urbanization, more older people, fewer White residents, and lower socioeconomic status (Zhang et al. 2019).[154] Reasons for the regional differences are unclear. Nationally, health impacts of temperature extremes often cluster in neighborhoods that are also poor, racially segregated, historically disinvested, and suffer other environmental problems such as air pollution.[155]

As extreme events become more frequent or severe in the Northeast, both rural and urban fenceline communities (those adjacent to industrial facilities) are expected to face increased health burdens from exposure to toxic pollution and stress related to potential chemical releases (KM 20.3).[156] In rural Pennsylvania, fenceline communities near oil and gas extraction activities show higher pediatric asthma and genital and urinary problems in non-elderly women; increased asthma is related also to industrial animal pollution.[157] Power sector carbon mitigation policies focusing on aggregate emissions reductions (e.g., Regional Greenhouse Gas Initiative) may not redress disparities in pollutant burdens.[158]

Energy insecurity is a complex problem influenced by social determinants of health and the changing climate. Energy burden—the fraction of household income spent on energy costs—varies among racial

groups, depending on energy type, end-use demand, and region, given differences in climate and households' socioeconomic characteristics. The cold Northeast climate leads to higher household energy burdens (compared with the Midwest, West, and South) based on residential energy consumption.[159] African American households had a heavier energy burden than others, but their energy poverty rate (the share of households paying a disproportionate share of income on the cost of energy use) decreased over time, whereas the rate for White households increased. Despite the substantial impact that energy burden can have on population health, links with climate change have been understudied.[160]

Continued warming in the Gulf of Maine ecosystem (KM 21.2) threatens access to species and locations of cultural significance. Some Tribal Nations and other coastal communities may have to shift their economic or subsistence harvests to new species that are migrating to the region, but the loss of other species or places is expected to result in a loss of cultural lifeways that will harm physical and mental health and well-being.[161]

Managed relocation from flood-prone areas is still relatively uncommon (KM 20.3), but initiatives such as the New Jersey Department of Environmental Protection's Superstorm Sandy Blue Acres Buyout Program are combining federal and state funding to support community relocation. Demand for buyouts (where homeowners sell properties to the government and the land is restored to open space) along the Mid-Atlantic seaboard relates to household-level perceptions of risk and confidence in ability to adapt to changing conditions.[162] Buyouts by local governments tend to be more common in counties with larger populations and income.[163] However, bought-out properties tend to be concentrated in areas of greater social vulnerabilities within the counties (i.e., relatively poorer, less densely populated areas with lower levels of education and English language proficiency and with greater racial diversity). The reasons underlying this pattern are unclear, but the finding highlights the need for evaluating the equity of buyout implementation and outcomes (KM 22.1).[164]

Social equity objectives that address challenges facing low-income communities and communities of color are prominent in local-level adaptation plans and initiatives.[165] These groups are less likely to have access to socioeconomic or healthcare resources to mitigate climate change impacts and are more likely to have preexisting health concerns, greater sensitivity to environmental changes, and higher exposure to pollution.[166]

Three dimensions of social equity are important in understanding uneven climate-related burdens. Distributive equity refers to the fair distribution of risks and benefits across groups; procedural equity focuses on the inclusion of affected groups prior to and during decision-making processes; and contextual equity reflects the preexisting structural, political, and socioeconomic conditions.[167,168]

Distributive equity has been a prominent theme in New York City's planning initiatives (e.g., OneNYC 2050). These plans cited the disproportionate health impacts of extreme temperatures on certain populations and focused heat mitigation investments on developing green space in underserved neighborhoods.[169] Local legislation mandated that city agencies work together and with local environmental justice leaders (addressing procedural equity) to publish more data on local environmental conditions, study environmental justice concerns, and publish a first-ever environmental justice plan that embeds a new approach to decision-making to counter historic injustices.[170,171] When representatives of frontline communities are included in the decision-making process (which helps address procedural equity), more attention is paid to the equitable distribution of benefits and burdens.[165]

Innovative sea level rise adaptation strategies developed by Tribal Nations, such as the WAMPUM Indigenous adaptation framework (Box 21.2), reflect Indigenous Knowledge typically not evident in other existing sea level rise adaptation frameworks in the Northeast.[172] Nonetheless, even when Tribal Nations work across jurisdictions to address climate change impacts, some adaptation plans do not take into

account Tribal Nations' interests in natural resources and areas of cultural significance. Tribal Nations face difficulties if adaptation strategies require relocating or reacquiring lands with access to cultural resources.[153] Relocation is a profoundly sensitive concern for Tribal Nations, given the history of forced migration and loss of homeland access. These past injustices highlight the importance of the United States' meeting trust and treaty obligations to Tribal Nations and ensuring that rights and access to original homelands, waters, and coasts are maintained and protected, even if these places become submerged.[152]

## Key Message 21.4

## Climate Action Plans Are Now Being Implemented

In recent years, there have been substantial advances in the magnitude and scope of climate action across all jurisdictional scales (*high confidence*). Almost every state in the region has conducted or updated a climate impact assessment, developed a comprehensive climate action plan, and enacted climate-related laws since 2018 (*high confidence*). Innovative approaches to transparent, inclusive, and equitable processes around climate action are being embraced by Tribes, municipalities, and states (*high confidence*). Although ambitious emissions reduction targets have been put forward, meeting these goals is expected to be challenging (*medium confidence*).

The landscape of climate action in the United States has been dynamic in recent years. The United States' withdrawal from and rejoining of the Paris Agreement raised questions among international and subnational constituencies about America's ability to meet its mitigation targets—and, as a consequence, catalyzed substantial climate action at state, city, business, and Tribal levels.[173,174] Moreover, the increase in public concern about community climate risks has led to a proliferation of vulnerability assessments and resilience plans among these subnational jurisdictions.[175]

A compilation of recent state-level climate impact assessment reports, climate action plans, and relevant laws and executive orders for the 12 states (plus Washington, DC) of the Northeast is shown in Table 21.1. For a more comprehensive assessment, see, for example, Dalal and Reidmiller (2023),[176] the US Climate Alliance inventory of member state policies particularly around mitigation,[177] the Georgetown Climate Center's State Adaptation Progress Tracker,[178] and the Northeast Region reports section of NOAA's Climate Resilience Toolkit.[179] The intent in presenting the information in this Key Message is to provide the ever-growing regional workforce (and related volunteer efforts) focusing on climate action planning and implementation with a concise, accessible source of information and inspiration as these workers develop, refine, and/or update their own assessments, plans, and climate-related laws. It endeavors to be a decision-support tool. An analysis of individual vulnerability assessments, climate action plans, or climate laws and executive orders is beyond the scope of this chapter; rather, the utility comes from providing—for the first time ever—a single resource compiling all of the Northeast's state- and Tribal-level information in one place. For a more comprehensive look at state-level climate mitigation policies across the entire country, see Key Message 32.5.

The Regional Greenhouse Gas Initiative (RGGI) is the largest regional climate coordination effort in the Northeast. RGGI includes every state in the Northeast region except West Virginia, but as of this writing, Pennsylvania's membership is undergoing a legal challenge. Established in 2005, RGGI was the Nation's first mandatory, market-based cap-and-trade program aimed at reducing $CO_2$ emissions from the power sector. RGGI issues a limited number of tradable $CO_2$ allowances with member states, which are then able to distribute the allowances through quarterly auctions. The revenue generated through these auctions goes toward investments in energy efficiency, renewable energy, and other consumer benefit programs. Although

there have been critiques of RGGI for, among other things, not adequately integrating environmental justice considerations (e.g., Declet-Barreto and Rosenberg 2022[158]), it has also been estimated that the program is responsible for an annual reduction of almost 5 million metric tons of $CO_2$[180] across the regulated states—roughly equivalent to the annual residential $CO_2$ emissions from Rhode Island and Maine combined.[181,182]

There has been strong cross-jurisdictional collaboration between the federal and state governments to advance climate resilience in the past few years. An example of this is the Federal Highway Administration's Resilience and Durability to Extreme Weather Pilot Project. Under this effort, departments of transportation and metropolitan planning organizations from eight states in the Northeast (ME, MA, CT, NY, NJ, PA, DE, and MD) are performing detailed vulnerability assessments to understand the condition of their transportation-related assets and the risks they face from climate change (KM 13.1).

In many Northeast states, particularly in New England, mitigation and adaptation action has been solidified in state law. Many states in the region have legally mandated greenhouse gas emissions reductions by midcentury, consistent with the goals of the Paris Agreement, and require state agencies to integrate the best available science (e.g., sea level rise projections) into land-use planning and zoning, building codes, and regulation development. Seven states in the region (ME, VT, MA, RI, CT, NY, and NJ) have laws requiring emissions reductions of at least 80% by 2050 (usually against a 1990 baseline). Several go even further in calling for economy-wide carbon neutrality before midcentury. Most of these laws have been passed by state legislatures since 2018. In other Northeast states, much of the action has been promulgated through executive order.[176]

Below are some novel climate actions employed by states in recent years that reflect increased attention to economic risks; equity considerations; and transparent, inclusive engagement processes (e.g., Molino et al. 2020;[183] Powell et al. 2019;[184] Reckien and Petkova 2019[185]). The list is illustrative, not exhaustive, but provides practitioners with examples of the latest innovative ways of advancing climate action at the state level.

- In Maine, the work of the Maine Climate Council and its Maine Won't Wait climate action plan was informed by a collection of economic impact and opportunity reports,[186] as well as an equity assessment conducted by an external team of experts.[187]
- In Massachusetts, a climate bill was passed that mandates that all new vehicles sold be zero emissions by 2035, as well as pilots a program allowing municipalities to ban fossil fuel connections (such as natural gas lines) to new construction.[188]
- Among other provisions, Rhode Island's H5445 requires the integration of environmental justice into climate action planning efforts to reduce impacts on vulnerable communities and create an equitable transition.[189]
- A Connecticut law allows municipalities to create stormwater authorities charged with developing stormwater management and public outreach.[190] Connecticut also enacted a first-in-the-Nation climate risk provision requiring the state insurance commissioner to submit a report on progress toward addressing climate-related risks, monitoring greenhouse gas levels, and bolstering resilience of insurers to the physical impacts of climate change.[191]
- In New York, the Climate Leadership and Community Protection Act established a Climate Justice Working Group to support the Climate Action Council in mainstreaming environmental justice considerations.[192] The New York State Common Retirement Fund released a Climate Action Plan Progress Report highlighting the fund's recent efforts to address climate risks and opportunities.[193]
- In New Jersey, a study was commissioned to better understand the integration of the needs and challenges of underrepresented and socially vulnerable populations into coastal hazards planning.[194]

- Maryland launched a Climate Leadership Academy in 2018, providing standardized climate training and support to state and local government officials, citizens, the private sector, and nonprofit organizations.[195]

**Table 21.1. Recent Climate Planning and Action Among States and Tribal Nations in the Northeast**

The table is a compilation of state and selected Tribal climate impact assessments and action plans, alongside illustrative climate-related laws, since 2018.

| State | Climate Impact Assessment | Climate Action Plan | Climate-Related Laws |
|---|---|---|---|
| **Maine** | Scientific Assessment of Climate Change and Its Effects in Maine[196]<br>Maine Climate Science Update 2021[197] | Maine Won't Wait[198] | An Act to Analyze the Impact of Sea Level Rise[199]<br>An Act to Implement Agency Recommendations Relating to Sea Level Rise and Climate Resilience[200]<br>An Act to Establish a Pilot Program to Encourage Climate Education in Maine Public Schools[201] |
| **New Hampshire** | New Hampshire Climate Assessment 2021[202] | N/A<br>(The state has a pre-2018 climate action plan[203]) | An Act Establishing a Coastal Resilience and Economic Development Program[204] |
| **Vermont** | Vermont Climate Assessment 2020[205] | Initial Vermont Climate Action Plan[206] | Global Warming Solutions Act[207] |
| **Massachusetts** | Massachusetts Climate Change Assessment[208] | Massachusetts Clean Energy and Climate Plan for 2025 and 2030[209]<br>Massachusetts State Hazard Mitigation and Climate Adaptation Plan[8] | An Act Creating a Next-Generation Roadmap for Massachusetts Climate Policy[210]<br>An Act Driving Clean Energy and Offshore Wind[188] |
| **Rhode Island** | Resilient Rhody: The Statewide Climate Resilience Action Strategy[211]<br>Rhode Island 2022 Climate Update to the 2016 GHG Emissions Reduction Plan[212]<br>Executive Climate Change Coordinating Council (EC4) to deliver "2025 Climate Strategy" by Dec 31, 2025 | Resilient Rhody: The Statewide Climate Resilience Action Strategy[211]<br>Rhode Island 2022 Climate Update to the 2016 GHG Emissions Reduction Plan[212]<br>Executive Climate Change Coordinating Council (EC4) to deliver "2025 Climate Strategy" by Dec 31, 2025 | 2021 Act on Climate[189] |
| **Connecticut** | Connecticut Physical Climate Science Assessment Report[213] | Taking Action on Climate Change and Building a More Resilient Connecticut for All[214] | An Act Concerning Climate Change Adaptation[190]<br>A provision to address climate-related risk to insurance[215] |

| State | Climate Impact Assessment | Climate Action Plan | Climate-Related Laws |
|---|---|---|---|
| **New York** | Observed and Projected Climate Change in New York State[216] | Draft Scoping Plan[217]<br>New York State Climate Action Council Scoping Plan[218] | Climate Leadership and Community Protection Act[192]<br>Soil Health and Climate Resiliency Act[219]<br>Green CHIPS[220]<br>Environmental Bond Act[221] |
| **Pennsylvania** | Pennsylvania Climate Impacts Assessment 2021[222] | Pennsylvania Climate Action Plan[223] | N/A |
| **New Jersey** | New Jersey's Rising Seas and Changing Coastal Storms[224]<br>2020 New Jersey Scientific Report on Climate Change[225]<br>Climate Change Impacts on Human Health and Communities[226] | 2021 New Jersey Climate Change Resilience Strategy[227]<br>2019 New Jersey Energy Master Plan[228]<br>New Jersey's Global Warming Response Act 80x50 Report[229] | An Act Concerning the Reduction of Greenhouse Gases[230]<br>An Act Requiring New Jersey to Join the U.S. Climate Alliance and Uphold the Paris Climate Accord[231] |
| **Delaware** | An Economic Analysis of the Impacts of Climate Change in the State of Delaware[232] | Delaware's Climate Action Plan[233] | Renewable Energy Portfolio Standards Act[234] |
| **Maryland** | Sea Level Rise Projections for Maryland 2018[235] | 2030 Greenhouse Gas Emissions Reduction Act Plan[236]<br>2021 Annual Report and Building Energy Transition Plan[237]<br>Maryland Ocean Acidification Action Plan 2020[135] | Climate Solutions Now Act[238]<br>Sea Level Rise Inundation and Coastal Flooding—Construction, Adaptation, and Mitigation[239] |
| **West Virginia** | N/A | N/A | N/A |
| **Washington, DC** | N/A<br>(DC has a pre-2018 impact assessment[240]) | Clean Energy DC[241]<br>Sustainable DC 2.0 Plan[242]<br>Resilient DC[243]<br>Climate Ready DC[244] | Clean Energy DC[241]<br>Sustainable DC 2.0 Plan[242]<br>Resilient DC[243]<br>Climate Ready DC[244] |
| **Saint Regis Mohawk Tribe** | Climate Change Adaptation Plan for Akwesasne[245] | Climate Change Adaptation Plan for Akwesasne[245] | N/A |
| **Shinnecock Indian Nation** | Shinnecock Indian Nation Climate Vulnerability Assessment and Action Plan[51] | Shinnecock Indian Nation Climate Vulnerability Assessment and Action Plan[51] | N/A |
| **Mi'kmaq Nation** | Thirteen Moons Climate Change Adaptation Plan[246] | Thirteen Moons Climate Change Adaptation Plan[246] | N/A |

## Box 21.1. Innovative Approaches to Climate Action at the Municipal Level

To complement the aforementioned focus on state-level planning and implementation—a jurisdictional level that was feasible to assess within the scope of this chapter—this box highlights examples of innovative approaches to climate action within mid-sized cities of the Northeast region. While extensive climate action planning and implementation has occurred within the major metropolitan areas of the Northeast region (e.g., Boston,[247] New York City,[169] and Philadelphia[248]), the focus here is on a geographically, economically, and politically diverse sampling of mid-sized cities that have different capacities (e.g., specialized staff, funding) to commit to the issue. Their efforts generally receive less visibility, but the need among similarly sized cities in the region—to learn about best practices and lessons learned in developing and implementing climate action plans to inform their own efforts—can be significant.

### Cross-Jurisdictional Climate Action Planning in Portland and South Portland, Maine

The cities of Portland and South Portland, Maine, are jointly producing assessments and plans to address climate change. The Climate Change Vulnerability Assessment report highlights the ways climate change is projected to affect Portland and South Portland, and the Our Contributions to Climate Change report contains data about their greenhouse gas emissions sources.[249,250] Informed by these foundational reports, the *One Climate Future* climate action and adaptation plan commits the two cities to reduce their greenhouse gas emissions by 80% from the 2017 level by 2050,[251] with municipal operations running on 100% renewable energy by 2040. Both city councils prioritize implementing the plan, working closely with municipal staff, business leaders, nonprofit organizations, and concerned citizens to ensure equitable and transparent progress is being made.

### Pittsburgh Climate Action Plan 3.0 and State of Sustainability Reports

Pittsburgh places climate action at the forefront of its municipal agenda through executive orders and planning efforts. Mayor William Peduto signed Executive Order 2017-08, in which the City of Pittsburgh endorsed and expressed its commitment to the "principles" of the Paris Agreement.[252] An executive order in April 2021 commits Pittsburgh to achieve carbon neutrality by 2050.[253] The city released an updated Climate Action Plan 3.0 in 2017, showcasing progress and adding new mitigation and adaptation measures.[254,255] The update process included multiyear civic engagements bringing together residents, the business community, the nonprofit sector, and local, state, and federal government partners.[256] The plan recognizes that climate-related stressors disproportionately affect some of the city's most vulnerable residents and focuses on co-benefits including improved equity. The city tracks progress through its Pittsburgh Equity Indicators report and produces annual State of Sustainability reports, highlighting progress on the Climate Action Plan.[257] The city's recently updated stormwater code requires new developments to reflect a future-climate-projected 10-year rainfall event instead of historically derived estimates.[258]

### Morgantown, West Virginia, Municipal Green Team Strategic Plan

While West Virginia has no formalized state-level mitigation or adaptation plan, the city of Morgantown committed to the Paris Agreement goals in August 2017. The Green Team, established in 2007, recommends actions to achieve the emissions-reduction goal,[259] advises the city council on environmental sustainability, and produces annual reports on the status of team projects.[260] In 2018, the Green Team released the Morgantown Municipal Green Team Strategic Plan (2018–2022), which contains a framework of goals and objectives that it plans to accomplish, including creating a climate action plan.[261] Lastly, the team has an energy policy guide, which contains recommendations to reduce the cost of energy and also highlights the costs of fossil fuel extraction and combustion on the environment, human health, and national security.[262]

## Box 21.2. Tribal Nations Leading and Setting an Example

### WAMPUM Adaptation Framework

The WAMPUM Adaptation Framework is a culturally responsive approach developed by Shinnecock Indian Nation citizen Dr. Kelsey Leonard for Northeast Indigenous Peoples impacted by sea level rise. This framework provides adaptation actions drawing from coastal Tribal Nations' Indigenous Knowledge systems. WAMPUM is an acronym for Witness (climate change warnings), Acknowledge (cultural relationships with land and water), Mend (areas damaged by sea level rise), Protect (cultural sites for future generations), Unite (with other Tribal Nations), and Move (to places out of harm's way but with cultural connections). The framework connects to wampum (carved quahog and whelk shells), which Tribal cultures in the Northeast have used for millennia for establishing diplomatic relations, documenting kinship, recording treaties, and negotiating the economic systems of settler European nations as currency. The WAMPUM framework acknowledges that sea level rise may force some Tribal nations and communities to relocate; however, the framework insists on Tribal self-determination in movement and continued rights, access, and cultural connections with areas inundated by sea level rise.[172]

### Climate Change Adaptation Plan for the Akwesasne/Saint Regis Mohawk Tribe

The Saint Regis Mohawk Tribe was the first Tribal Nation in the Northeast to formally draft a climate change adaptation plan, which was published in 2013. The plan was initiated by the Tribal Nation's Environment Division to investigate the local impacts of climate change and to provide recommendations for adaptation actions. This plan continues to be implemented and is noted for its grounding in the cultural framework and priorities of the Saint Regis Mohawk Tribe.[245]

### Shinnecock Indian Nation Climate Vulnerability Assessment and Action Plan

Shinnecock translates to "People of the Stony Shore." The Shinnecock Indian Nation, located on eastern Long Island, completed a climate change adaptation plan following Hurricane Sandy and updated it in 2019. The Shinnecock Indian Nation has a 1-square-mile reservation with more than 600 residents; it is vulnerable to sea level rise, storms, flooding, and coastal erosion. Other climate change concerns include water quality issues from increasing temperatures, salinity changes, and acidification. The Shinnecock are closely tied to the coast, and fish and shellfish have been a staple of traditional diets for thousands of years.[51] The updated Shinnecock Indian Nation Climate Vulnerability Assessment and Action Plan includes several steps, including evaluation of adaptation actions, habitat restoration, green infrastructure projects, land conservation, and outreach and education on climate change.

### Mi'kmaq Nation: Thirteen Moons Climate Change Adaptation Plan

The Mi'kmaq Nation is one of several Tribal Nations of the Wabanaki Confederacy ("People of the Dawn"). The Mi'kmaq Nation (formerly known as the Aroostook Band of Micmacs) live in northern Maine in Aroostook County. In February 2022, the Tribal council approved its Thirteen Moons Climate Change Adaptation Plan. The primary concern for the Mi'kmaq Nation is warming winters, which are encouraging the spread of invasive species that damage forest health (e.g., emerald ash borer) and harming animal populations (e.g., winter tick impact on moose). The plan calls for proactive efforts to address climate change, such as the development of solar energy, community education and outreach on climate change, and forest and wildlife health monitoring.[246]

## Key Message 21.5

## Implementation of Climate Plans Depends on Adequate Financing

Options for financing mitigation and adaptation efforts have expanded in recent years, providing households, communities, and businesses with more options for responding to climate change (*high confidence*). Flood insurance allows individuals and communities to recover following extreme flooding events, but many at-risk homeowners lack adequate coverage (*high confidence*). Although the public sector remains the primary source of funding for adaptation, private capital has started to invest in a variety of mitigation and adaptation projects, including services for monitoring climate risks and community-based catastrophe insurance (*high confidence*).

Climate adaptation plans and resilience projects ultimately need financing to come to fruition. Although finance is just one piece of the climate adaptation puzzle, progress and innovation in recent years have expanded the options available to businesses, communities, and Tribal organizations to cover the cost of building resiliently for the future.[263] Implementing adaptation plans also requires meeting prerequisite conditions. Political leadership and local trust must be built among all stakeholders to ensure a common vision and successful outcome, and technical expertise is needed to execute the plan.[264] Sources of private capital also look for transparency, well-defined risk metrics, and an adequate return on investment.[265]

Successful projects often require a mix of funding sources, and financing via a mixed or stacked approach becomes increasingly necessary as project size grows (KM 31.6).[266] A stacked approach also helps spread the burden and benefits across multiple parties to achieve mutually beneficial mitigation and adaptation goals, improved distribution of risk management functions, and increasing private equity participation in climate adaptation activities.[265]

Currently, access to private funding of climate mitigation and adaptation remains primarily limited to large businesses and institutional investors, as their focus remains on protecting corporate investments and limiting potential liability, not the equitable distribution of climate mitigation and adaptation funds.[267] Federal and state public funding of climate mitigation and adaptation—whether via grants, loans, or tax assessments—is currently available to a wider array of stakeholders and is more readily accessible to over-burdened communities (e.g., EPA 2023[268]).

For households and businesses, property insurance remains one of the most effective risk financing mechanisms for protection from both natural catastrophes and the impacts of climate change.[269] Insurance provides individuals, businesses, and communities a source of financial resilience from natural disasters, annually providing billions of dollars in recovery funds to devastated communities across the United States.[270] Despite paying approximately $661 billion (in 2022 dollars) in insurance claims from natural disasters between 2012 and 2021, the US property and casualty insurance industry remains very well capitalized, with a record $978 billion (in 2022 dollars) in policyholder surplus to pay claims from future catastrophic events.[271]

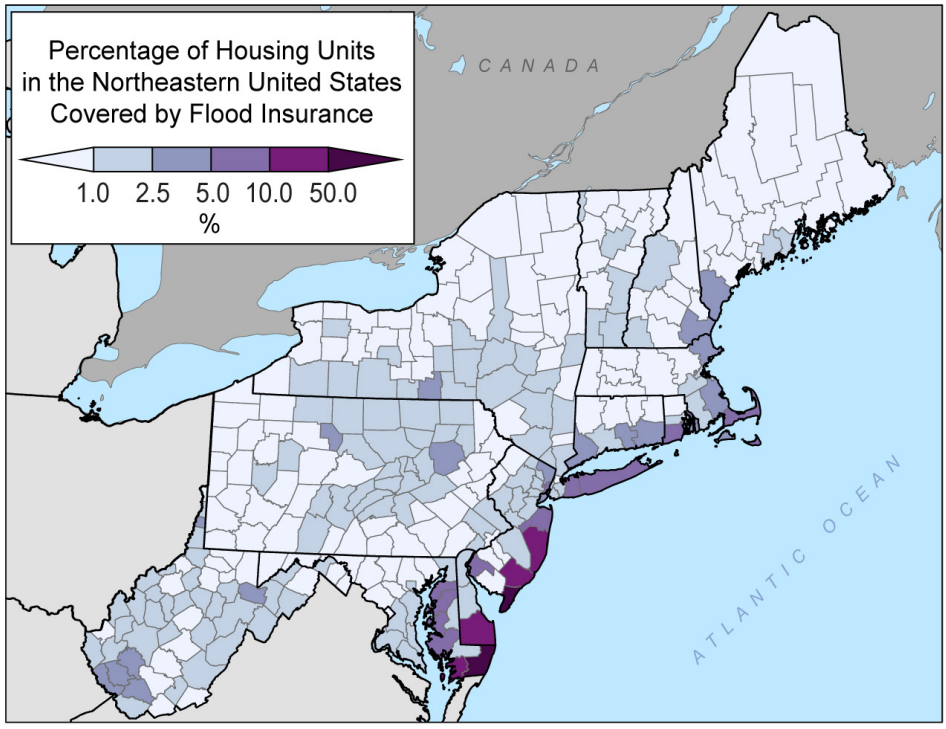
However, insurance take-up rates (the percentage of households who purchase insurance) vary greatly by natural hazard. While about 50% of fire and wind damage in the United States is covered by insurance, only 12%–14% of flood damage is insured by the federally run National Flood Insurance Program (NFIP).[272] This "gap" in flood insurance coverage leaves millions at risk of financial hardship as the frequency and severity of coastal and rainfall flood events across the Northeast are expected to increase (KM 21.1).[273] In 1978–2015, 6 of the top 17 states with the highest NFIP payouts were in the Northeast, with New Jersey and New York ranked third and fourth, respectively.[274] Currently only two counties in the Northeast have flood insurance

take-up rates above 50%. No other northeastern county exceeds 20% take-up, averaging 6.5% along the coast and 1.3% inland (Figure 21.9).

Lack of flood insurance coverage is driven by affordability issues and the underestimation of flood risk by individuals. Misperceptions around FEMA flood maps play a significant role here, as most individuals are unaware that the maps are not holistic in their assessment of flood risk. While FEMA is updating maps, some are still decades old and unrepresentative of total flood risk. Additionally, the maps do not consider flood risk along smaller catchments, nor do they consider the potential for localized flooding from intense rainfall events.[275] Flood risk data for overburdened and Tribal communities have historically been underrepresented in flood mapping as well (KMs 16.1, 20.1). Since flood insurance is not required by mortgage lenders outside of mapped FEMA-designated Special Flood Hazard Areas (SFHAs; locations with an annual probability of flooding of 1% or more), many homeowners in non-mapped SFHAs or prone to flash flooding believe that they are not at risk and thus forego coverage.[276]

Even for those who purchase NFIP coverage, policy limits are capped by law at $250,000 for residential structures, well below the current median value for an existing single-family dwelling in the Northeast ($366,000), potentially leaving policyholders financially exposed if their homes are completely destroyed.[277,278] Enforcement of flood insurance requirements is another issue, as lenders often do not continue to verify coverage in locations where flood insurance is required; as a result, about one-third of policyholders stop purchasing coverage after three years.[279]

## Flood Insurance Take-Up Rates by County




**Many Northeast households and communities risk financial hardship from a lack of flood insurance coverage.**

**Figure 21.9.** The figure shows flood insurance take-up rates by county in the northeastern United States, based on 2020 Census housing units and active National Flood Insurance Program policy counts at the end of 2021. Almost half of the counties in the region have less than 1% market penetration, while only two counties (Cape May, New Jersey, and Worchester, Maryland) have more than 50% of their housing units insured for flood. The lack of coverage, particularly inland, leaves both individuals and communities at risk of major financial hardship after a flood event. Figure credit: Munich Reinsurance America Inc.

Because of major flooding events associated with hurricanes—including Irene, Sandy, and Ida in the Northeast—NFIP remains more than $20 billion in debt to the US Treasury, despite $16 billion in debt forgiveness by the federal government in 2017. This debt is driven by the program's concentration of vulnerable risks along the coast and subsidized premiums that were unable to cover the claims volume from multiple large flood events.[280] In response, the NFIP has developed a new pricing methodology, Risk Rating 2.0, with a goal of making premiums better reflect the level of flood risk at individual locations.[281] Additionally, the NFIP started purchasing catastrophe reinsurance in 2017 and catastrophe bonds in 2018, which together can provide more than $1 billion in claims-paying capacity if losses to the NFIP exceed $10 billion from an extreme flood event.[282]

Under the new Risk Rating 2.0 system, the majority of NFIP policyholders were projected to see only a nominal change in premiums, with only 4% of policyholders expected to see larger increases.[281] However, the move toward risk-adequate rates exacerbates affordability issues, especially for vulnerable individuals and communities (KM 9.3). To address rising costs, some states have used public funds to help individuals in vulnerable communities afford flood insurance. For example, in 2019, the state of New York reduced property taxes for lower-income households to make flood insurance more affordable.[263] Private insurers, who mostly stopped underwriting flood insurance for homeowners and small businesses in 1968, are also starting to reenter this market as more sophisticated flood risk assessment tools become available.[283]

Beyond flood insurance, private-sector financing of climate mitigation and adaptation has increased by 13% globally since 2018, with an annual average expenditure of $332 billion (in 2022 dollars). Of that total, about $85 billion (in 2022 dollars) has been invested annually in the United States and Canada. However, the vast majority of this private capital, nearly 98%, is currently being spent on mitigation, focused on solar and onshore wind energy development, electric vehicle infrastructure, and increasing adoption of electric vehicles.[264]

The current dearth of private-sector investment in climate adaptation, despite ample capital available for such projects, is the result of several business obstacles, including a lack of localized climate data on which to make sound investment decisions, a lack of well-defined performance metrics, and the perception that returns on investment from adaptation projects are insufficient.[265] It also can be challenging for private investors to identify climate adaptation projects that might be financially attractive to them, and, similarly, communities might not know how to find sources of private capital.[264]

Although the private sector's direct investment in climate adaptation remains small, the sector is playing an increasing role in enabling adaptation. Over the past four years, dozens of companies have started providing climate adaptation services, including high-resolution risk assessments, the deployment of sensors for risk monitoring, and innovative finance and risk transfer mechanisms.[265] This private sector investment in adaptation not only helps others but also ultimately makes businesses' own supply chains more resilient to potential climate shocks (Focus on Risks to Supply Chains).[265]

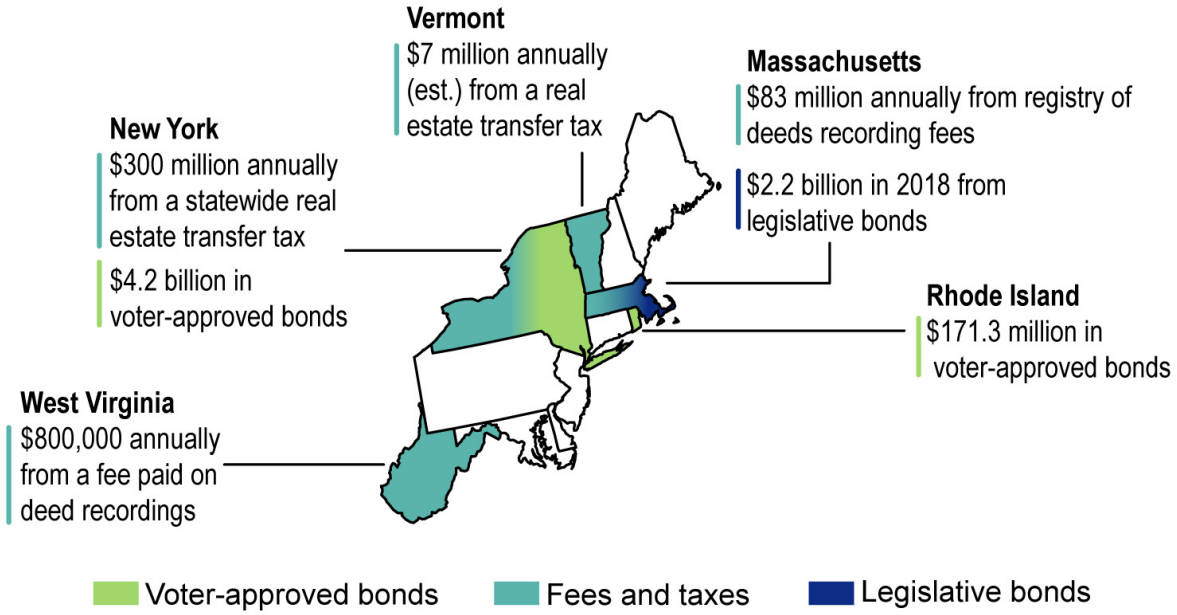
Recent innovations around the financing of climate adaptation by the private sector include community-based catastrophe insurance (CBCI), climate adaptation as a service, and climate investment intermediaries. A CBCI is a community institution (it does not have to be governmental) that helps its members access and afford insurance. The level of involvement by the community institution can vary, from purchasing a group policy on behalf of its members, to creating its own risk-bearing entity, to simply facilitating access to insurance for its members.[263] Climate adaptation as a service allows for the longer-term financing of climate adaptation projects for businesses and communities, with investors repaid over time with interest. Climate investment intermediaries are entities that facilitate matching asset owners with investors interested in climate adaptation projects.[284]

The public sector has historically shouldered the costs related to investments in the built environment.[285] State and local governments are the primary owners and operators of transportation and water systems, spending $216.5 billion on projects in 2019, substantially more than federal spending at $173.3 billion (both amounts in 2022 dollars).[286] The investments represent the responsibility of local entities to ensure continuous operation and services provided to taxpayers.

Providing these services becomes increasingly difficult when dealing with an aging and inefficient infrastructure coupled with climate change. This challenge is highlighted in the American Society of Civil Engineers' 2021 America's Infrastructure Report Card, in which no Northeast state received a grade higher than C.[287] Additionally, state and local officials are finding it challenging to proactively address resilience planning due to limited staff and inconsistent budgeting.

Historic levels of federal funding directed to states, counties, Tribes, and communities through pandemic relief provide access to needed capital for climate resilience. The Infrastructure Investment and Jobs Act of 2021 provides funding through low-interest loan programs such as the Clean Water and Drinking Water State Revolving Funds.[288] Capacity barriers exist to accessing federal funds, especially for Indigenous Peoples (KM 16.2). Increased capacity across these state-administered loan programs and access to grants create opportunities for Northeast states to address deferred maintenance and accelerate project implementation. Additionally, states in the Northeast continue to issue general obligation bonds through statewide ballot measures to finance climate resilience projects (Figure 21.10). Success of voter-approved bonds requires diverse stakeholder engagement. For example, land trusts are uniquely positioned in the Northeast to be effective in quickly generating support from landowners to elected officials for climate adaptation and mitigation funding and projects.[289]

## Public Funding for Resilience




**Northeastern states provide funding for resilience efforts in a number of ways.**

**Figure 21.10.** Northeastern states fund planning and implementation of resilience projects through multiple public financing mechanisms. Examples of voter approved bonds, taxes and fees, and legislative bonds established and ongoing since 2018 are highlighted. The most common source of state funding originates from annual fees and is largely directed to conservation and natural and working lands. Infrastructure projects and capital investments are most often funded through voter-approved general obligation bonds, with Rhode Island being the most active issuer of bonds for climate-resilience projects. Figure credit: Rhode Island Infrastructure Bank.

While access to infrastructure financing is increasing, the public sector's ability and willingness to repay debt financing is a common challenge. This is heightened by the influx of federal stimulus funding, as well as local governments waiting for potential grant funds. New and innovative financing models that spread credit risk across multiple payors and focus on outcomes have moved from concept to reality. Most deals have focused on stormwater investments to increase installation of nature-based solutions and address regulatory compliance. For example, the Buffalo Sewer Authority financed nature-based solution projects through a $54 million environmental impact bond to support the city's Rain Check 2.0 initiative.[290] Buffalo Sewer will utilize bond proceeds for the design, engineering, and construction of stormwater projects that should reduce combined sewer overflows, improving water quality and community resilience.

As Northeast states plan investment priorities, a pipeline of climate-resilience projects often does not exist. However, there have been recent examples of leadership in Massachusetts, Maine, and Rhode Island to create programs focused on identifying and prioritizing resilience projects. These programs have generated more than $130 million (in 2022 dollars) in state-directed funding for planning and resilience projects from 2018 to 2022. The overall need identified through these planning programs far outweighs the grant funding available and highlights the opportunity to link these priorities with other financing programs.

# Traceable Accounts

## *Process Description*

Chapter leadership compiled a list of previous Fourth National Climate Assessment (NCA4) authors and those provided to chapter leadership through the USGCRP author nomination process. They defined potential themes for the region based on their own and potential author expertise, NOAA engagements over a decade in the region via Regional Climate Services, and a literature review. They prioritized invitations to author candidates based on their ability to address potential themes and a desire for diversity based on a mix of regional distribution, career stage, gender, sector, discipline, race, and ethnicity. Where gaps existed, chapter leadership identified additions to the candidate list through professional networks, research into departments at key regional institutions, and searches on several databases of experts from frontline communities. Introductory conversations were pursued to gauge interest and answer questions. In some cases, when author candidates indicated they could not participate, chapter leadership asked them for recommendations of additional candidates.

Author meetings were held on a weekly basis throughout the process, with a Gantt chart used to track tasks and interim milestones. Authors were divided into teams based on expertise and Key Message, and some held team meetings in addition to the full chapter meetings. The author team used productivity tools to gain consensus on key themes for the Zero Order Draft. A public workshop on January 26, 2022, was held virtually, with productivity tools used to synthesize public input provided. Key Message teams then used workshop input and literature review to further develop their Key Messages and develop figures.

## Key Message 21.1

## Chronic Impacts of Extreme Weather Are Shaping Adaptation and Mitigation Efforts

### Description of Evidence Base

Literature reviewed (gathered by using tools such as the Web of Science) discussed an increase in extreme events in the region and the impacts caused by these events.[10,11,12,21] Authors anchored their understanding of climate trends, likelihood, and confidence in climate data analysis through discussions with the Chapter 2 author team and the Technical Support Unit (TSU) science team. Authors frequently referenced descriptive statistics and graphs from the NCA Figure and Climate Data Generator, developed by the TSU, and from NOAA NCEI's Climate at a Glance. Cost data for recovery from incidents were used as a metric for impacts. For each state and Tribe in the region, the author team searched for the following types of documents and reviewed any that were found: heat vulnerability maps, climate action plans, hazard management plans, flood maps, and weather-relevant toolkits. The team also searched state and Tribal websites for information about responses to large storms that had recently occurred in the region. Most states and some Tribes and local governments have documented some evidence of climate planning, but the methods and types of documentation widely varied. It was rarer to find clear links to recent weather events, but comprehensive understanding of the planning process illuminates these events as motivators for climate adaptation and mitigation efforts. For example, an increase in public planning meetings and changes in funding allocations can be tracked to follow a particularly impactful storm event.

### Major Uncertainties and Research Gaps

Our understanding of changes in extreme precipitation is largely based on analyses and descriptive statistics showing observed and projected changes of daily precipitation time series. Research into trends

in sub-daily and sub-hourly precipitation patterns in the region is ongoing but still inconclusive. The comprehensive body of state, local, and regional-level responses to climate change is continuously evolving and has not been summarized in any one place. This makes it difficult to quantitatively evaluate trends in climate action at different levels of government and to determine whether specific types of climate action can be generally attributed to the occurrence of specific extreme events.

### Description of Confidence and Likelihood

*High confidence* in ongoing increases in the frequency of extreme weather, specifically precipitation, is based on both published literature analyzing daily weather trends through time and current NOAA data. These increases in extreme weather frequency were deemed *very likely* based upon evidence on precipitation and heatwaves presented in Chapter 2, with this likelihood determined to maintain consistency across chapters. The conclusion that problematic flooding is *very likely* due to extreme precipitation was determined through actual event tracking based on knowledge of storms, NOAA NCEI's database (https://www.ncdc.noaa.gov/stormevents/), and newspaper searches. Efforts to address climate change through adaptation and mitigation are also determined through web searches that show both news reports and multiple efforts that include mitigation planning. *High confidence* regarding the increase of adaptation and mitigation activities across the region, including natural and nature-based features, comes from less formal web searches, personal knowledge, and author team discussions. *Medium confidence* in the influence of extreme events on adaptation and mitigation efforts is based on the balance of evidence discovered when searching for attribution of reasons for planning and implementing these efforts.

## Key Message 21.2

## Ocean and Coastal Impacts Are Driving Adaptation to Climate Change

### Description of Evidence Base

There has been a significant growth of peer-reviewed literature since NCA4 on climate change impacts on ocean and coastal environments in the Northeast. Ocean temperatures have increased,[291] and several marine heatwaves[65] have occurred in the region. These changes have impacted the marine ecosystem from phytoplankton to whales, with consequent effects on fisheries and the fishing community.[59] Coastal forests in some parts of the region have been affected by saltwater intrusion due to sea level rise, transforming them into tidal marshes.[122] Documentation on climate adaptation has come through formal reports and peer-reviewed literature in the field.

### Major Uncertainties and Research Gaps

The responses of the coastal and marine food webs to the effects of multiple stressors (e.g., warming, marine heatwaves, loss of oxygen, and acidification) in the Northeast are currently not well understood. Additional research would help to fill knowledge gaps on the relative severity of these stressors on estuarine coastal ocean ecosystems and to evaluate the effectiveness of nature-based solutions with regard to ameliorating the impacts of sea level rise in coastal environments.

### Description of Confidence and Likelihood

Confidence in the statements that the coastal ocean is warming, sea levels are rising, and ocean acidification is increasing is assessed as being *high* based on a synthesis of the published literature and formal reports. For marine heatwaves the confidence level is *high* based on peer-reviewed papers that covered limited data over a shorter time period. The statement on the existence of shifts in distribution, productivity and seasonal timing of life-cycle events of some marine species is made with *high confidence* based on

information contained in several peer-reviewed publications. For adaptation actions, the confidence level is *high* based on actions taken across state, local, and federal scales.

## Key Message 21.3

## Disproportionate Impacts Highlight the Importance of Equitable Policy Choices

### Description of Evidence Base

Reports of statistically significant relationships among sociodemographic variables and health and well-being outcomes related to heat, flooding, and storm events are published in peer-reviewed journals.[147] There is a growing body of literature that supports the conclusion that racial and ethnic minorities and low- and moderate-income communities are disproportionately impacted by climate extremes while having less access to the resources needed to mitigate those impacts.[148,151,159] Evidence of social equity as a priority in local climate adaptation planning is provided in publicly available plans published by government agencies and nongovernment organizations.[165] Specific actions to address environmental justice challenges are provided in the plans.[172]

### Major Uncertainties and Research Gaps

The complex relationships among the changing climate, sociodemographic characteristics of communities, and health and well-being outcomes are multifaceted, and no single study can capture all aspects of these relationships. Moreover, longitudinal studies are rare, but they would help capture evolving patterns of impacts and responses within individuals and to evaluate the effectiveness of communities' adaptation initiatives. There are gaps in knowledge about the equity impacts of alternative adaptation options.

### Description of Confidence and Likelihood

Confidence in the statement that climate-related hazards are causing disproportionate impacts among racial and ethnic minorities and low- and moderate-income communities in the Northeast is assessed as being *very high* because it is based on the synthesis of many peer-reviewed papers and formal reports. Confidence in the statement that these disproportionately impacted communities tend to have less access to resources and face higher environmental and health burdens is assessed as being *high* because it is based on the synthesis of many peer-reviewed papers, but the relationships are hard to tease apart. The assessment of *high confidence* in the statement that social equity objectives are prominent in many local-level adaptation initiatives but that progress toward equitable outcomes remains uncertain is based on the availability of several example plans, as well as insufficient time to permit robust assessment of equity outcomes. The likelihood of observed changes and events is assessed as *very likely* based on observations of extreme weather events and official actions and the synthesis of peer-reviewed papers and formal reports.

## Key Message 21.4

## Climate Action Plans Are Now Being Implemented

### Description of Evidence Base

The evidence base assessed for this Key Message includes formally adopted reports, plans, executive orders, and laws addressing climate risks and vulnerabilities, sources of greenhouse gas emissions, and response options from state, municipal, and Tribal governments, including the Dalal and Reidmiller (2023)[176] assessment of state-level climate actions. While state-level differences in impacts are revealed through state-specific climate impact assessments (see references in Table 21.1), broadly speaking the observed and

projected climate impacts are similar across states in the Northeast region. The state-by-state assessment of climate action revealed that most states in the region have taken ambitious, aggressive climate action through both the legislative and executive branches of government, with Pennsylvania (legislative inaction) and West Virginia (legislative and executive inaction) standing out as distinctly different. The reader is directed to Table 21.1 for a suite of state-specific resources describing climate impacts, sources of greenhouse gas emissions, and various state-government-level climate actions.

### Major Uncertainties and Research Gaps

While the statements in the Key Message do not contain traditional research uncertainties, there are unknowns, including the following: Have jurisdictions adequately and comprehensively assessed their climate-related risk exposure? How much uncertainty is associated with the greenhouse gas emissions inventories that have been conducted? Are there cascading impacts or interacting stressors that are not yet accounted for? Several major unknowns will persist in any such analysis: Will the jurisdiction achieve the targets that have been set forth? What future level of warming will these jurisdictions experience? Will the anticipated impacts manifest as projected? Will jurisdictions be able to overcome nonfinancial barriers to adaptation? Will adaptation actions prove to be effective against realized impacts?

### Description of Confidence and Likelihood

Confidence in most of the statements in the Key Message is assessed as being *high* because they represent an assessment of many stand-alone reports, plans, and laws. The exception to this is the final statement regarding whether mitigation targets will be met, which is assessed as having *medium confidence*, as the authors were unable to identify literature analyzing projections of emissions for each of the states in the region. Likelihood is not assessed in this Key Message because the nature of the content being assessed does not lend itself to a probabilistic assessment of the uncertainty associated with the statements.

## Key Message 21.5

## Implementation of Climate Plans Depends on Adequate Financing

### Description of Evidence Base

Currently, the quality of the information is high and comes from reliable academic sources, federal agencies, and nongovernmental organizations. Data regarding FEMA and the National Flood Insurance Program (NFIP) are sourced directly from those entities based on the most recent data available.[280,281] However, most private risk financing and public funding information is not found in peer-reviewed literature but rather in gray literature, white papers, and case studies.[264,265] Unlike the public sector, the private sector typically does not announce adaptation work they might be financing or investing in.[264] However, the concepts behind public- and private-sector mitigation and adaptation projects are available from reliable academic and NGO sources.[263,284]

### Major Uncertainties and Research Gaps

The literature searches for the draft of this chapter unfortunately did not produce any specific examples of private-sector adaptation investment in the Northeast, for the reasons stated in the previous section. Community-based catastrophe insurance is a new financial risk transfer concept. Few extant in-force examples exist, and ultimately the concept may not gain widespread use (see Bernhardt et al. 2021[263]). Similarly, climate investment intermediaries are also a new business concept but ultimately may not achieve long-term success.[265] The recent increase in federal funding through the Infrastructure Investment and Jobs Act[288] provides opportunity to pay for climate resilience projects, but the public sector's ability and willingness to repay debt financing is uncertain.

## Description of Confidence and Likelihood

This section primarily discusses human financial systems and adaptation to mitigate physical climate change risk. Confidence around impacts of the flood insurance gap is *high*, based on the low market penetration of flood insurance across the Northeast (Figure 21.9) and the fact that the NFIP policies are currently capped by law at $250,000 for structural damage,[277] far below the median cost of a single-family home in 2022.[278] The confidence around demand for climate resilience investment is *high*, as numerous Northeast states have established programs to develop a project pipeline and pass voter-approved general obligation bonds to fund project implementation (Figure 21.10). Confidence around climate impacts is *high*, based on a literature search similar to that for Key Message 21.1.[13,20,23]

# References


1. U.S. Census Bureau. 2021: S2401, Occupation By Sex for the Civilian Employed Population 16 Years and Over: American Community Survey 1-Year Estimates. U.S. Department of Commerce, U.S. Census Bureau. https://data.census.gov/table?q=S2401&tid=ACSST5Y2021.S2401

2. 2020 Census Redistricting Data. U.S. Census Bureau, Pub. L. No. 94-171, August 12, 2021. https://data.census.gov/table?q=2020+population&tid=DECENNIALPL2020.P1

3. U.S. Census Bureau. 2011: Decennial Census: 2010 DEC Summary File 1. U.S. Department of Commerce, U.S. Census Bureau. https://data.census.gov/cedsci/table?q=2010%20population&tid=decennialsf12010.p1

4. Dupigny-Giroux, L.A., E.L. Mecray, M.D. Lemcke-Stampone, G.A. Hodgkins, E.E. Lentz, K.E. Mills, E.D. Lane, R. Miller, D.Y. Hollinger, W.D. Solecki, G.A. Wellenius, P.E. Sheffield, A.B. MacDonald, and C. Caldwell, 2018: Ch. 18. Northeast. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 669–742. https://doi.org/10.7930/nca4.2018.ch18

5. HUD, n.d.: Hurricane Sandy Rebuilding Task Force: Rebuild by Design. U.S. Department of Housing and Urban Development. https://www.hud.gov/sandyrebuilding/rebuildbydesign

6. HUD, 2016: National Disaster Resilience Competition: Grantee Profiles. U.S. Department of Housing and Urban Development. https://www.hud.gov/sites/documents/NDRCGRANTPROFILES.PDF

7. New York State Governor's Office of Storm Recovery, n.d.: Living with the Bay. State of New York. https://stormrecovery.ny.gov/living-bay

8. Commonwealth of Massachusetts, 2018: Massachusetts State Hazard Mitigation and Climate Adaptation Plan. Commonwealth of Massachusetts. https://www.mass.gov/info-details/massachusetts-integrated-state-hazard-mitigation-and-climate-adaptation-plan

9. González, J.E., L. Ortiz, B.K. Smith, N. Devineni, B. Colle, J.F. Booth, A. Ravindranath, L. Rivera, R. Horton, K. Towey, Y. Kushnir, D. Manley, D. Bader, and C. Rosenzweig, 2019: New York City Panel on Climate Change 2019 report chapter 2: New methods for assessing extreme temperatures, heavy downpours, and drought. *Annals of the New York Academy of Sciences*, **1439** (1), 30–70. https://doi.org/10.1111/nyas.14007

10. Howarth, M.E., C.D. Thorncroft, and L.F. Bosart, 2019: Changes in extreme precipitation in the Northeast United States: 1979–2014. *Journal of Hydrometeorology*, **20** (4), 673–689. https://doi.org/10.1175/jhm-d-18-0155.1

11. Huang, H., C.M. Patricola, J.M. Winter, E.C. Osterberg, and J.S. Mankin, 2021: Rise in Northeast US extreme precipitation caused by Atlantic variability and climate change. *Weather and Climate Extremes*, **33**, 100351. https://doi.org/10.1016/j.wace.2021.100351

12. Huang, H., J.M. Winter, and E.C. Osterberg, 2018: Mechanisms of abrupt extreme precipitation change over the northeastern United States. *Journal of Geophysical Research: Atmospheres*, **123** (14), 7179–7192. https://doi.org/10.1029/2017jd028136

13. Tabari, H., 2020: Climate change impact on flood and extreme precipitation increases with water availability. *Scientific Reports*, **10** (1), 13768. https://doi.org/10.1038/s41598-020-70816-2

14. City of New York, 2021: The New Normal: Combating Storm-Related Extreme Weather in New York City. City of New York, Office of the Deputy Mayor for Administration, 66 pp. https://www.nyc.gov/assets/orr/pdf/publications/WeatherReport.pdf

15. Krakauer, N.Y., T. Lakhankar, and D. Hudson, 2019: Trends in drought over the northeast United States. *Water*, **11** (9), 1834. https://doi.org/10.3390/w11091834

16. Albano, C.M., J.T. Abatzoglou, D.J. McEvoy, J.L. Huntington, C.G. Morton, M.D. Dettinger, and T.J. Ott, 2022: A Multidataset assessment of climatic drivers and uncertainties of recent trends in evaporative demand across the continental United States. *Journal of Hydrometeorology*, **23** (4), 505–519. https://doi.org/10.1175/jhm-d-21-0163.1

17. Barai, K., R. Tasnim, B. Hall, P. Rahimzadeh-Bajgiran, and Y.-J. Zhang, 2021: Is drought increasing in Maine and hurting wild blueberry production? *Climate*, **9** (12). https://doi.org/10.3390/cli9120178

18. Lane, D., E. Murdock, K. Genskow, C. Rumery Betz, and A. Chatrchyan, 2019: Climate change and dairy in New York and Wisconsin: Risk perceptions, vulnerability, and adaptation among farmers and advisors. *Sustainability*, **11** (13). https://doi.org/10.3390/su11133599

19. Contosta, A.R., A. Adolph, D. Burchsted, E. Burakowski, M. Green, D. Guerra, M. Albert, J. Dibb, M. Martin, W.H. McDowell, M. Routhier, C. Wake, R. Whitaker, and W. Wollheim, 2017: A longer vernal window: The role of winter coldness and snowpack in driving spring transitions and lags. *Global Change Biology*, **23** (4), 1610–1625. https://doi.org/10.1111/gcb.13517

20. Dahl, K., R. Licker, J.T. Abatzoglou, and J. Declet-Barreto, 2019: Increased frequency of and population exposure to extreme heat index days in the United States during the 21st century. *Environmental Research Communications*, **1** (7), 075002. https://doi.org/10.1088/2515-7620/ab27cf

21. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

22. Foster, S., R. Leichenko, K.H. Nguyen, R. Blake, H. Kunreuther, M. Madajewicz, E.P. Petkova, R. Zimmerman, C. Corbin-Mark, E. Yeampierre, A. Tovar, C. Herrera, and D. Ravenborg, 2019: New York City Panel on Climate Change 2019 Report Chapter 6: Community-based assessments of adaptation and equity. *Annals of the New York Academy of Sciences*, **1439** (1), 126–173. https://doi.org/10.1111/nyas.14009

23. Wolfe, D.W., A.T. DeGaetano, G.M. Peck, M. Carey, L.H. Ziska, J. Lea-Cox, A.R. Kemanian, M.P. Hoffmann, and D.Y. Hollinger, 2018: Unique challenges and opportunities for northeastern US crop production in a changing climate. *Climatic Change*, **146** (1–2), 231–245. https://doi.org/10.1007/s10584-017-2109-7

24. Anderson, G.B., K.W. Oleson, B. Jones, and R.D. Peng, 2018: Projected trends in high-mortality heatwaves under different scenarios of climate, population, and adaptation in 82 US communities. *Climatic Change*, **146** (3-4), 455–470. https://doi.org/10.1007/s10584-016-1779-x

25. Agel, L., M. Barlow, C. Skinner, F. Colby, and J. Cohen, 2021: Four distinct northeast US heat wave circulation patterns and associated mechanisms, trends, and electric usage. *npj Climate and Atmospheric Science*, **4** (1), 31. https://doi.org/10.1038/s41612-021-00186-7

26. Rosenzweig, B.R., L. McPhillips, H. Chang, C. Cheng, C. Welty, M. Matsler, D. Iwaniec, and C.I. Davidson, 2018: Pluvial flood risk and opportunities for resilience. *Wiley Interdisciplinary Reviews: Water*, **5** (6), 1302. https://doi.org/10.1002/wat2.1302

27. Beven II, J.L., A. Hagen, and R. Berg, 2022: National Hurricane Center Tropical Cyclone Report: Hurricane Ida. National Oceanic and Atmospheric Administration, National Weather Service, National Hurricane Center, 163 pp. https://www.nhc.noaa.gov/data/tcr/AL092021_Ida.pdf

28. National Academies of Sciences, Engineering, and Medicine, 2019: *Framing the Challenge of Urban Flooding in the United States*. The National Academies Press, Washington, DC, 100 pp. https://doi.org/10.17226/25381

29. EPA, 2021: Baltimore Urban Waters Flood Science and Policy Workshop Action Report. EPA 840-R-21-004. U.S. Environmental Protection Agency, 14 pp. https://www.epa.gov/system/files/documents/2021-09/baltimore-flood-report-9.27.21_508_1.pdf

30. Ross, A.C., C.A. Stock, D. Adams-Smith, K. Dixon, K.L. Findell, V. Saba, and B. Vogt, 2021: Anthropogenic influences on extreme annual streamflow into Chesapeake Bay from the Susquehanna River. *Bulletin of the American Meteorological Society*, **102** (1), 25–32. https://doi.org/10.1175/bams-d-20-0129.1

31. Sun, N., M.S. Wigmosta, D. Judi, Z. Yang, Z. Xiao, and T. Wang, 2021: Climatological analysis of tropical cyclone impacts on hydrological extremes in the Mid-Atlantic region of the United States. *Environmental Research Letters*, **16** (12), 124009. https://doi.org/10.1088/1748-9326/ac2d6a

32. Booth, J.F., V. Narinesingh, K.L. Towey, and J. Jeyaratnam, 2021: Storm surge, blocking, and cyclones: A compound hazards analysis for the northeast United States. *Journal of Applied Meteorology and Climatology*, **60** (11), 1531–1544. https://doi.org/10.1175/jamc-d-21-0062.1

33. Lin, N., R. Marsooli, and B.A. Colle, 2019: Storm surge return levels induced by mid-to-late-twenty-first-century extratropical cyclones in the Northeastern United States. *Climatic Change*, **154** (1), 143–158. https://doi.org/10.1007/s10584-019-02431-8

34. Mayo, T.L. and N. Lin, 2022: Climate change impacts to the coastal flood hazard in the northeastern United States. *Weather and Climate Extremes*, **36**, 100453. https://doi.org/10.1016/j.wace.2022.100453

35. Rutgers University, 2023: NJ Forest Adapt. Rutgers University, Agricultural Experiment Station. https://njforestadapt.rutgers.edu/#/select

36. 2021: Mitigation Planning. 44 C.F.R. § 201. https://www.ecfr.gov/current/title-44/chapter-I/subchapter-D/part-201

37. FEMA, 2022: State Mitigation Planning Policy Guide. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_state-mitigation-planning-policy-guide_042022.pdf

38. FEMA, 2022: Local Mitigation Planning Policy Guide. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_local-mitigation-planning-policy-guide_042022.pdf

39. TNC, 2021: Promoting Nature-Based Hazard Mitigation Through FEMA Mitigation Grants. The Nature Conservancy and AECOM. https://www.nature.org/content/dam/tnc/nature/en/documents/Promoting-Nature-Based-Hazard-Mitigation-Through-FEMA-Mitigation-Grants-05-10-2021-LR.pdf

40. Natural Areas Conservancy, 2021: Improving Coastal Resilience [Webpage]. https://naturalareasnyc.org/wetlands

41. Sheng, Y.P., V.A. Paramygin, A.A. Rivera-Nieves, R. Zou, S. Fernald, T. Hall, and K. Jacob, 2022: Coastal marshes provide valuable protection for coastal communities from storm-induced wave, flood, and structural loss in a changing climate. *Scientific Reports*, **12** (1), 3051. https://doi.org/10.1038/s41598-022-06850-z

42. Abualfaraj, N., J. Cataldo, Y. Elborolosy, D. Fagan, S. Woerdeman, T. Carson, and F.A. Montalto, 2018: Monitoring and modeling the long-term rainfall-runoff response of the Jacob K. Javits Center green roof. *Water*, **10** (11), 1494. https://doi.org/10.3390/w10111494

43. Catalano de Sousa, M.R., F.A. Montalto, and P. Gurian, 2016: Evaluating green infrastructure stormwater capture performance under extreme precipitation. *Journal of Extreme Events*, **03** (02), 1650006. https://doi.org/10.1142/s2345737616500068

44. Roseboro, A., M.N. Torres, Z. Zhu, and A.J. Rabideau, 2021: The impacts of climate change and porous pavements on combined sewer overflows: A case study of the city of Buffalo, New York, USA. *Frontiers in Water*, **3**, 725174. https://doi.org/10.3389/frwa.2021.725174

45. Smalls-Mantey, L. and F. Montalto, 2021: The seasonal microclimate trends of a large scale extensive green roof. *Building and Environment*, **197**, 107792. https://doi.org/10.1016/j.buildenv.2021.107792

46. TNC, 2021: New Coalition "Forest for All NYC" Releases NYC Urban Forest Agenda. The Nature Conservancy. https://www.nature.org/en-us/newsroom/ny-forest-for-all-nyc-urban-forest-agenda/

47. Catalano de Sousa, M.R., F.A. Montalto, and M.I. Palmer, 2016: Potential climate change impacts on green infrastructure vegetation. *Urban Forestry & Urban Greening*, **20**, 128–139. https://doi.org/10.1016/j.ufug.2016.08.014

48. Lewellyn, C. and B. Wadzuk, 2019: Evaluating the risk-based performance of bioinfiltration facilities under climate change scenarios. *Water*, **11** (9), 1765. https://doi.org/10.3390/w11091765

49. Shevade, L.J., L.J. Lo, and F.A. Montalto, 2020: Numerical 3D model development and validation of curb-cut inlet for efficiency prediction. *Water*, **12** (6), 1791. https://doi.org/10.3390/w12061791

50. Wong, S.M., P.L. Gurian, J. Daley, H. Bostrom, M. Matsil, and F.A. Montalto, 2020: A preliminary assessment of coastal GI's role during Hurricane Sandy: A case study of three communities. *Urban Water Journal*, **17** (4), 356–367. https://doi.org/10.1080/1573062x.2020.1781909

51. Anchor QEA, The Nature Conservancy, and Fine Arts and Sciences, 2019: Shinnecock Indian Nation Climate Vulnerability Assessment and Action Plan. Shinnecock Indian Nation and Peconic Estuary Program. https://www.peconicestuary.org/wp-content/uploads/2019/10/Shinnecock-Indian-Nation-Climate-Vulnerability-Assessment-and-Action-Plan.pdf

52. EPA, 2018: Popponesset Bay Restoration Project Improves Water via Oyster Propagation. EPA 160F18001. U.S. Environmental Protection Agency, American Indian Environmental Office, Washington, DC. https://www.epa.gov/sites/default/files/2020-05/documents/r1_mashpee_gap_success.pdf

53. Wampanoag Tribe, 2023: Lobsterville Road Beachgrass Project. Wampanoag Tribe of Gay Head (Aquinnah), Natural Resources Department, Aquinnah, MA. https://wampanoagtribe-nsn.gov/projects

54. Daigneault, A., E. Simons-Legaard, S. Birthisel, J. Carroll, I. Fernandez, and A. Weiskittel, 2020: Maine Forestry and Agriculture Natural Climate Solutions Mitigation Potential: Interim Report. University of Maine, School of Forest Resources, Augusta, ME. https://doi.org/10.13140/RG.2.2.16604.00649

55. Fargione, J.E., S. Bassett, T. Boucher, S.D. Bridgham, R.T. Conant, S.C. Cook-patton, P.W. Ellis, A. Falcucci, J.W. Fourqurean, T. Gopalakrishna, H. Gu, B. Henderson, M.D. Hurteau, K.D. Kroeger, T. Kroeger, T.J. Lark, S.M. Leavitt, G. Lomax, R.I. McDonald, J.P. Megonigal, D.A. Miteva, C.J. Richardson, J. Sanderman, D. Shoch, S.A. Spawn, J.W. Veldman, C.A. WIlliams, P.B. Woodbury, C. Zganjar, M. Baranski, R.A. Houghton, E. Landis, E. McGlynn, W.H. Schlesinger, J.V. Siikamakiariana, E. Sutton-Grierand, and B.W. Griscom, 2018: Natural climate solutions for the United States. *Science Advances*, **4** (11), 1869. https://doi.org/10.1126/sciadv.aat1869

56. Osaka, S., R. Bellamy, and N. Castree, 2021: Framing "nature-based" solutions to climate change. *WIREs Climate Change*, **12** (5), e729. https://doi.org/10.1002/wcc.729

57. NEFSC, 2022: State of the Ecosystem 2022: New England. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center. https://doi.org/10.25923/ypv2-mw79

58. NEFSC, 2022: State of the Ecosystem 2022: Mid-Atlantic. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center. https://doi.org/10.25923/5s5y-0h81

59. Pershing, A.J., M.A. Alexander, D.C. Brady, D. Brickman, E.N. Curchitser, A.W. Diamond, McClenachan, L., , K.E. Mills, O.C. Nichols, D.E. Pendleton, N.R. Record, J.D. Scott, M.D. Staudinger, and Y. Wang, 2021: Climate impacts on the Gulf of Maine ecosystem: A review of observed and expected changes in 2050 from rising temperatures. *Elementa: Science of the Anthropocene*, **9** (1), 00076. https://doi.org/10.1525/elementa.2020.00076

60. Weiskopf, S.R., M.A. Rubenstein, L.G. Crozier, S. Gaichas, R. Griffis, J.E. Halofsky, K.J. Hyde, T.L. Morelli, J.T. Morisette, R.C. Muñoz, A.J. Pershing, D.L. Petersone, R. Poudel, M.D. Staudinger, A.E. Sutton-Grier, L. Thompson, J. Vose, J.F. Weltzin, and K.P. Whyte, 2020: Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, **733**, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782

61. Lotze, H.K., S. Mellon, J. Coyne, M. Betts, M. Burchell, K. Fennel, M.A. Dusseault, S.D. Fuller, E. Galbraith, L.G. Suarez, L.d. Gelleke, N. Golombek, B. Kelly, S.D. Kuehn, E. Oliver, M. MacKinnon, W. Muraoka, I.T.G. Predham, K. Rutherford, N. Shackell, O. Sherwood, E.C. Sibert, and M. Kienast, 2022: Long-term ocean and resource dynamics in a hotspot of climate change. FACETS, **7**, 1142–1184. https://doi.org/10.1139/facets-2021-0197

62. Karmalkar, A.V. and R.M. Horton, 2021: Drivers of exceptional coastal warming in the northeastern United States. *Nature Climate Change*, **11** (10), 854–860. https://doi.org/10.1038/s41558-021-01159-7

63. Neto, A.G., J.A. Langan, and J.B. Palter, 2021: Changes in the Gulf Stream preceded rapid warming of the Northwest Atlantic shelf. *Communications Earth & Environment*, **2** (1), 74. https://doi.org/10.1038/s43247-021-00143-5

64. Mills, K.E., A.J. Pershing, C.J. Brown, Y. Chen, F.-S. Chiang, D.S. Holland, S. Lehuta, J.A. Nye, J.C. Sun, A.C. Thomas, and R.A. Wahle, 2013: Fisheries management in a changing climate: Lessons from the 2012 ocean heat wave in the northwest Atlantic. *Oceanography*, **26** (2), 191–195. https://doi.org/10.5670/oceanog.2013.27

65. Perez, E., S. Ryan, M. Andres, G. Gawarkiewicz, C.C. Ummenhofer, J. Bane, and S. Haines, 2021: Understanding physical drivers of the 2015/16 marine heatwaves in the Northwest Atlantic. *Scientific Reports*, **11**, 17623. https://doi.org/10.1038/s41598-021-97012-0

66. Gawarkiewicz, G.C., K., J. Forsyth, F. Bahr, A.M. Mercer, A. Ellertson, P. Fratantoni, H. Seim, S. Haines, and L. Han, 2019: Characteristics of an advective marine heatwave in the Middle Atlantic Bight in early 2017. *Frontiers in Marine Science*, **6**, 712. https://doi.org/10.3389/fmars.2019.00712

67. Chen, Z. and E.N. Curchitser, 2020: Interannual variability of the Mid-Atlantic Bight cold pool. *Journal of Geophysical Research: Oceans*, **125** (8), e2020JC016445. https://doi.org/10.1029/2020jc016445

68. NEFSC, 2021: State of the Ecosystem 2021: New England Revised. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center. https://doi.org/10.25923/6pww-mw45

69. Sorochan, K.A., S. Plourde, R. Morse, P. Pepin, J. Runge, C. Thompson, and C.L. Johnson, 2019: North Atlantic right whale (*Eubalaena glacialis*) and its food: (II) interannual variations in biomass of *Calanus* spp. on western North Atlantic shelves. *Journal of Plankton Research*, **41** (5), 687–708. https://doi.org/10.1093/plankt/fbz044

70. Charif, R.A., Y. Shiu, C.A. Muirhead, C.W. Clark, S.E. Parks, and A.N. Rice, 2020: Phenological changes in North Atlantic right whale habitat use in Massachusetts Bay. *Global Change Biology*, **26** (2), 734–745. https://doi.org/10.1111/gcb.14867

71. Record, N.R., J.A. Runge, D.E. Pendleton, W.M. Balch, K.T.A. Davies, A.J. Pershing, C.L. Johnson, K. Stamieszkin, R. Ji, Z. Feng, S.D. Kraus, R.D. Kenney, C.A. Hudak, C.A. Mayo, C. Chen, J.E. Salisbury, and C.R.S. Thompson, 2019: Rapid climate-driven circulation changes threaten conservation of endangered North Atlantic right whales. *Oceanography*, **32** (2), 162–169. https://doi.org/10.5670/oceanog.2019.201

72. Hobday, A.J., L.V. Alexander, S.E. Perkins, D.A. Smale, S.C. Straub, E.C.J. Oliver, J.A. Benthuysen, M.T. Burrows, M.G. Donat, M. Feng, N.J. Holbrook, P.J. Moore, H.A. Scannell, A. Sen Gupta, and T. Wernberg, 2016: A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, **141**, 227–238. https://doi.org/10.1016/j.pocean.2015.12.014

73. GMRI, 2022: Gulf of Maine warming update: 2021 the hottest year on record. Gulf of Maine Research Institute, Portland, ME, March 28, 2022. https://gmri.org/stories/warming-21/#:~:text=Annual%20Sea%20Surface%20Temperatures,a%20remarkable%200.5%20%C2%B0F

74. McBride, R.S., M.K. Tweedie, and K. Oliveira, 2018: Reproduction, first-year growth, and expansion of spawning and nursery grounds of black sea bass (*Centropristis striata*) into a warming Gulf of Maine. *Fishery Bulletin*, **116**, 323–336. https://doi.org/10.7755/fb.116.3-4.10

75. McMahan, M.D., G.D. Sherwood, and J.H. Grabowski, 2020: Geographic variation in life-history traits of black sea bass (*Centropristis striata*) during a rapid range expansion. *Frontiers in Marine Science*, **7**, 567758. https://doi.org/10.3389/fmars.2020.567758

76. Timbs, J.R., E.N. Powell, and R. Mann, 2019: Changes in the spatial distribution and anatomy of a range shift for the Atlantic surfclam *Spisula solidissima* in the Mid-Atlantic Bight and on Georges Bank. *Marine Ecology Progress Series*, **620**, 77–97. https://doi.org/10.3354/meps12964

77. Torre, M.P., K.R. Tanaka, and Y. Chen, 2018: A spatiotemporal evaluation of Atlantic sea scallop *Placopecten magellanicus* habitat in the Gulf of Maine using a bioclimate envelope model. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science*, **10** (2), 224–235. https://doi.org/10.1002/mcf2.10022

78. McManus, M.C., J.A. Hare, D.E. Richardson, and J.S. Collie, 2018: Tracking shifts in Atlantic mackerel (*Scomber scombrus*) larval habitat suitability on the Northeast U.S. Continental Shelf. *Fisheries Oceanography*, **27** (1), 49–62. https://doi.org/10.1111/fog.12233

79. Allyn, A.J., M.A. Alexander, B.S. Franklin, F. MassiotGranier, A.J. Pershing, J.D. Scott, and K.E. Mills, 2020: Comparing and synthesizing quantitative distribution models and qualitative vulnerability assessments to project marine species distributions under climate change. *PLoS One*, **15** (4), 0231595. https://doi.org/10.1371/journal.pone.0231595

80. Record, N.R., W.M. Balch, and K. Stamieszkin, 2019: Century-scale changes in phytoplankton phenology in the Gulf of Maine. *PeerJ*, **7**, 6735. https://doi.org/10.7717/peerj.6735

81. Dalton, R.M., J.J. Sheppard, J.T. Finn, A. Jordaan, and M.D. Staudinger, 2022: Phenological variation in spring migration timing of adult alewife in coastal Massachusetts. *Marine and Coastal Fisheries*, **14** (2), e10198. https://doi.org/10.1002/mcf2.10198

82. Lombardo, S.M., J.A. Buckel, E.F. Hain, E.H. Griffith, and H. White, 2020: Evidence for temperature-dependent shifts in spawning times of anadromous alewife (*Alosa pseudoharengus*) and blueback herring (*Alosa aestivalis*). *Canadian Journal of Fisheries and Aquatic Sciences*, **77** (4), 741–751. https://doi.org/10.1139/cjfas-2019-0140

83. Staudinger, M.D., K.E. Mills, K. Stamieszkin, N.R. Record, C.A. Hudak, A. Allyn, A. Diamond, K.D. Friedland, W. Golet, M.E. Henderson, C.M. Hernandez, T.G. Huntington, R. Ji, C.L. Johnson, D.S. Johnson, A. Jordaan, J. Kocik, Y. Li, M. Liebman, O.C. Nichols, D. Pendleton, R.A. Richards, T. Robben, A.C. Thomas, H.J. Walsh, and K. Yakola, 2019: It's about time: A synthesis of changing phenology in the Gulf of Maine ecosystem. *Fisheries Oceanography*, **28** (5), 532–566. https://doi.org/10.1111/fog.12429

84. Langan, J.A., G. Puggioni, C.A. Oviatt, M.E. Henderson, and J.S. Collie, 2021: Climate alters the migration phenology of coastal marine species. *Marine Ecology Progress Series*, **660**, 1–18. https://doi.org/10.3354/meps13612

85. Griffin, L.P., C.R. Griffin, J.T. Finn, R.L. Prescott, M. Faherty, B.M. Still, and A.J. Danylchuk, 2019: Warming seas increase cold-stunning events for Kemp's Ridley sea turtles in the northwest Atlantic. *PLoS One*, **14** (1), 0211503. https://doi.org/10.1371/journal.pone.0211503

86. Groner, M.L., J.D. Shields, D.F. Landers Jr, J. Swenarton, and J.M. Hoenig, 2018: Rising temperatures, molting phenology, and epizootic shell disease in the American lobster. *The American Naturalist*, **192** (5), 163–177. https://doi.org/10.1086/699478

87. Shields, J.D., 2019: Climate change enhances disease processes in crustaceans: Case studies in lobsters, crabs, and shrimps. *Journal of Crustacean Biology*, **39** (6), 673–683. https://doi.org/10.1093/jcbiol/ruz072

88. Zhao, M., D.C. Behringer, J. Bojko, A.S. Kough, L. Plough, C.P.D. Tavares, A. Aguilar-Perera, O.S. Reynoso, G. Seepersad, O. Maharaj, M.B. Sanders, D. Carnales, G. Fabiano, D. Carnevia, M.A. Freeman, N.A.M. Atherley, L.D. Medero-Hernández, and E.J. Schott, 2020: Climate and season are associated with prevalence and distribution of trans-hemispheric blue crab reovirus (*Callinectes sapidus* reovirus 1). *Marine Ecology Progress Series*, **647**, 123–133. https://doi.org/10.3354/meps13405

89. Anderson, D.M., E. Fensin, C.J. Gobler, A.E. Hoeglund, K.A. Hubbard, D.M. Kulis, J.H. Landsberg, K.A. Lefebvre, P. Provoost, M.L. Richlen, J.L. Smith, A.R. Solow, and V.L. Trainer, 2021: Marine harmful algal blooms (HABs) in the United States: History, current status and future trends. *Harmful Algae*, **102**, 101975. https://doi.org/10.1016/j.hal.2021.101975

90. Griffith, A.W., O.M. Doherty, and C.J. Gobler, 2019: Ocean warming along temperate western boundaries of the Northern Hemisphere promotes an expansion of *Cochlodinium polykrikoides* blooms. *Proceedings of the Royal Society B*, **286** (1904), 20190340. https://doi.org/10.1098/rspb.2019.0340

91. Griffith, A.W., S.E. Shumway, and C.J. Gobler, 2019: Differential mortality of North Atlantic bivalve molluscs during harmful algal blooms caused by the dinoflagellate, *Cochlodinium* (a.k.a. Margalefidinium) polykrikoides. *Estuaries Coasts*, **42** (1), 190–203. https://doi.org/10.1007/s12237-018-0445-0

92. Li, M., W. Ni, F. Zhang, P.M. Glibert, and C.-H. Lin, 2020: Climate-induced interannual variability and projected change of two harmful algal bloom taxa in Chesapeake Bay, USA. *Science of The Total Environment*, **744**, 140947. https://doi.org/10.1016/j.scitotenv.2020.140947

93. Zhang, F., M. Li, P.M. Glibert, and S.H. Ahn, 2021: A three-dimensional mechanistic model of *Prorocentrum minimum* blooms in eutrophic Chesapeake Bay. *Science of The Total Environment*, **769**, 144528. https://doi.org/10.1016/j.scitotenv.2020.144528

94. Parveen, S., J. Jacobs, G. Ozbay, K. Chintapenta, E. Almuhaideb, J. Meredith, S. Ossai, A. Abbott, A. Grant, K. Brohawn, P. Chigbu, and G.P. Richards, 2020: Seasonal and geographical differences in total and pathogenic *Vibrio parahaemolyticus* and *Vibrio vulnificus* levels in seawater and oysters from the Delaware and Chesapeake Bays determined using several methods. *Applied and Environmental Microbiology*, **86** (23), 01581–20. https://doi.org/10.1128/aem.01581-20

95. Olson, E. and J.M. Vasslides, 2022: Multi-decadal declines and species assemblage shifts in the fish community of a northeast US temperate estuary. *Estuaries and Coasts*, **45** (7), 2219–2240. https://doi.org/10.1007/s12237-022-01078-6

96. Schonfeld, A.J., J. Gartland, and R.J. Latour, 2022: Spatial differences in estuarine utilization by seasonally resident species in Mid-Atlantic Bight, USA. *Fisheries Oceanography*, **31** (6), 615–628. https://doi.org/10.1111/fog.12611

97. Chigbu, P., L. Malinis, H. Malagon, and S. Doctor, 2019: Influence of temperature on the occurrence and distribution of the sand shrimp *Crangon septemspinosa* (Decapoda: Caridea: Crangonidae) in polyhaline lagoons in Maryland, USA. *Journal of Crustacean Biology*, **39** (5), 586–593. https://doi.org/10.1093/jcbiol/ruz045

98. Doctor, S., G. Tyler, C. Weedon, and A. Willey, 2020: Investigation of Maryland's Coastal Bays and Atlantic Ocean Finfish Stocks. Final Report, F-50-R-28. Maryland Department of Natural Resources, Annapolis, MD. https://dnr.maryland.gov/fisheries/documents/f-50-r-28_july%202019_june%202020_report_sept28.pdf

99. Tuckey, T.D., J.L. Swinford, M.C. Fabrizio, H.J. Small, and J.D. Shields, 2021: Penaeid shrimp in Chesapeake Bay: Population growth and black gill disease syndrome. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science*, **13** (3), 159–173. https://doi.org/10.1002/mcf2.10143

100. Glandon, H.L., K.H. Kilbourne, and T.J. Miller, 2019: Winter is (not) coming: Warming temperatures will affect the overwinter behavior and survival of blue crab. *PLoS ONE*, **14** (7), 0219555. https://doi.org/10.1371/journal.pone.0219555

101. Xu, Y.-Y., W.-J. Cai, R. Wanninkhof, J. Salisbury, J. Reimer, and B. Chen, 2020: Long-term changes of carbonate chemistry variables along the North American East Coast. *Journal of Geophysical Research: Oceans*, **125** (7), e2019JC015982. https://doi.org/10.1029/2019jc015982

102. Siedlecki, S.A., J. Salisbury, D.K. Gledhill, C. Bastidas, S. Meseck, K. McGarry, C.W. Hunt, M. Alexander, D. Lavoie, Z.A. Wang, J. Scott, D.C. Brady, I. Mlsna, K. Azetsu-Scott, C.M. Liberti, D.C. Melrose, M.M. White, A. Pershing, D. Vandemark, D.W. Townsend, C. Chen, W. Mook, and R. Morrison, 2021: Projecting ocean acidification impacts for the Gulf of Maine to 2050: New tools and expectations. *Elementa: Science of the Anthropocene*, **9** (1), 00062. https://doi.org/10.1525/elementa.2020.00062

103. Rheuban, J.E., S.C. Doney, S.R. Cooley, and D.R. Hart, 2018: Projected impacts of future climate change, ocean acidification, and management on the US Atlantic sea scallop (*Placopecten magellanicus*) fishery. *PLoS One*, **13** (9), 0203536. https://doi.org/10.1371/journal.pone.0203536

104. Claret, M., E.D. Galbraith, J.B. Palter, D. Bianchi, K. Fennel, D. Gilbert, and J.P. Dunne, 2018: Rapid coastal deoxygenation due to ocean circulation shift in the northwest Atlantic. *Nature Climate Change*, **8**, 868–872. https://doi.org/10.1038/s41558-018-0263-1

105. Gilbert, D., N.N. Rabalais, R.J. Díaz, and J. Zhang, 2010: Evidence for greater oxygen decline rates in the coastal ocean than in the open ocean. *Biogeosciences*, **7** (7), 2283–2296. https://doi.org/10.5194/bg-7-2283-2010

106. Schmidtko, S., L. Stramma, and M. Visbeck, 2017: Decline in global oceanic oxygen content during the past five decades. *Nature*, **542** (7641), 335–339. https://doi.org/10.1038/nature21399

107. Pitcher, G.C., A. Aguirre-Velarde, D. Breitburg, J. Cardich, J. Carstensen, D.J. Conley, B. Dewitte, A. Engel, D. Espinoza-Morriberón, G. Flores, V. Garçon, M. Graco, M. Grégoire, D. Gutiérrez, J.M. Hernandez-Ayon, H.-H.M. Huang, K. Isensee, M.E. Jacinto, L. Levin, A. Lorenzo, E. Machu, L. Merma, I. Montes, N. Swa, A. Paulmier, M. Roman, K. Rose, R. Hood, N.N. Rabalais, A.G.V. Salvanes, R. Salvatteci, S. Sánchez, A. Sifeddine, A.W. Tall, A.K. van der Plas, M. Yasuhara, J. Zhang, and Z.Y. Zhu, 2021: System controls of coastal and open ocean oxygen depletion. *Progress in Oceanography*, **197**, 102613. https://doi.org/10.1016/j.pocean.2021.102613

108. Hinson, K.E., M.A.M. Friedrichs, P. St-Laurent, F. Da, and R.G. Najjar, 2022: Extent and causes of Chesapeake Bay warming. JAWRA *Journal of the American Water Resources Association*, **58** (6), 805–825. https://doi.org/10.1111/1752-1688.12916

109. Mazzini, P.L.F. and C. Pianca, 2022: Marine heatwaves in the Chesapeake Bay. *Frontiers in Marine Science*, **8**, 750265. https://doi.org/10.3389/fmars.2021.750265

110. Frankel, L.T., M.A.M. Friedrichs, P. St-Laurent, A.J. Bever, R.N. Lipcius, G. Bhatt, and G.W. Shenk, 2022: Nitrogen reductions have decreased hypoxia in the Chesapeake Bay: Evidence from empirical and numerical modeling. *Science of The Total Environment*, **814**, 152722. https://doi.org/10.1016/j.scitotenv.2021.152722

111. Ni, W., M. Li, and J.M. Testa, 2020: Discerning effects of warming, sea level rise and nutrient management on long-term hypoxia trends in Chesapeake Bay. *Science of The Total Environment*, **737**, 139717. https://doi.org/10.1016/j.scitotenv.2020.139717

112. Marban, P.R., J.M. Mullinax, J.P. Resop, and D.J. Prosser, 2019: Assessing beach and island habitat loss in the Chesapeake Bay and Delmarva coastal bay region, USA, through processing of Landsat imagery: A case study. *Remote Sensing Applications: Society and Environment*, **16**, 100265. https://doi.org/10.1016/j.rsase.2019.100265

113. Borrell, S.J. and J.A. Puleo, 2019: In situ hydrodynamic and morphodynamic measurements during extreme storm events. *Shore & Beach*, **87** (4), 23–30. https://doi.org/10.34237/1008743

114. Swanston, C., L.A. Brandt, M.K. Janowiak, S.D. Handler, P. Butler-Leopold, L. Iverson, F.R. Thompson III, T.A. Ontl, and P.D. Shannon, 2018: Vulnerability of forests of the Midwest and Northeast United States to climate change. *Climatic Change*, **146** (1), 103–116. https://doi.org/10.1007/s10584-017-2065-2

115. Weissman, D.S. and K.L. Tully, 2020: Saltwater intrusion affects nutrient concentrations in soil porewater and surface waters of coastal habitats. *Ecosphere*, **11** (2), 03041. https://doi.org/10.1002/ecs2.3041

116. Gibson, N., S. McNulty, C. Miller, M. Gavazzi, E. Worley, D. Keesee, and D. Hollinger, 2021: Identification, Mitigation, and Adaptation to Salinization on Working Lands in the U.S. Southeast. Gen. Tech. Rep. SRS-259. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 69 pp. https://doi.org/10.2737/srs-gtr-259

117. Carleton, G.B., 2021: Simulation of Potential Water Allocation Changes, Cape May County, New Jersey. Scientific Investigations Report 2020-5052. U.S. Geological Survey, Reston, VA, 39 pp. https://doi.org/10.3133/sir20205052

118. Paul, M.J., R. Coffey, J. Stamp, and T. Johnson, 2019: A review of water quality responses to air temperature and precipitation changes 1: Flow, water temperature, saltwater intrusion. *JAWRA Journal of the American Water Resources Association*, **55** (4), 824–843. https://doi.org/10.1111/1752-1688.12710

119. Breitenother, A., K.M. Laumann, A. Carew, and H. Kelsey, 2022: Maryland Coastal Adaptation Report Card 2021. Maryland Department of Natural Resources, Maryland Coastal Zone Management Program. https://www.adaptationclearinghouse.org/resources/maryland-coastal-adaptation-report-card-2021.html

120. Kearney, W.S., A. Fernandes, and S. Fagherazzi, 2019: Sea-level rise and storm surges structure coastal forests into persistence and regeneration niches. *PloS One*, **14** (5), 0215977. https://doi.org/10.1371/journal.pone.0215977

121. Kirwan, M.L. and K.B. Gedan, 2019: Sea-level driven land conversion and the formation of ghost forests. *Nature Climate Change*, **9** (6), 450–457. https://doi.org/10.1038/s41558-019-0488-7

122. Sacatelli, R., R.G. Lathrop, and M. Kaplan, 2020: Impacts of Climate Change on Coastal Forests in the Northeast US. Rutgers University, New Brunswick, NJ, 48 pp. https://doi.org/10.7282/t3-n4tn-ah53

123. Able, K.W., 2021: From Cedar cemeteries to marsh lakes: A case study of sea-level rise and habitat change in a northeastern US salt marsh. *Estuaries and Coasts*, **44**, 1649–1657. https://doi.org/10.1007/s12237-021-00946-x

124. Brickman, D., M.A. Alexander, A.J. Pershing, J.D. Scott, and Z. Wang, 2021: Projections of physical conditions in the Gulf of Maine in 2050. *Elementa: Science of the Anthropocene*, **9** (1), 00055. https://doi.org/10.1525/elementa.2020.20.00055

125. Tanaka, K.R., M.P. Torre, V.S. Saba, C.A. Stock, and Y. Chen, 2020: An ensemble high-resolution projection of changes in the future habitat of American lobster and sea scallop in the northeast US continental shelf. *Diversity and Distributions*, **26** (8), 987–1001. https://doi.org/10.1111/ddi.13069

126. Chowdhury, M.S.N., M. La Peyre, L.D. Coen, R.L. Morris, M.W. Luckenbach, T. Ysebaert, B. Walles, and A.C. Smaal, 2021: Ecological engineering with oysters enhances coastal resilience efforts. *Ecological Engineering*, **169**, 106320. https://doi.org/10.1016/j.ecoleng.2021.106320

127. O'Donoghue, S., M. Lehmann, D. Major, G. Major-Ex, C. Sutherland, A. Motau, N. Haddaden, A.S.M.G. Kibria, R. Costanza, C. Groves, A. Behie, and K. Johnson, 2021: Adaptation to climate change in small coastal cities: The influence of development status on adaptation response. *Ocean and Coastal Management*, **211**, 105788. https://doi.org/10.1016/j.ocecoaman.2021.105788

128. Balasubramanayam, V. and K. Howard, 2019: New Hampshire Living Shoreline Site Suitability Assessment: Technical Report. R-WD-19-19. Prepared for the New Hampshire Department of Environmental Services Coastal Program, Portsmouth, NH. https://www.des.nh.gov/water/coastal-waters/living-shorelines

129. Coastal and Marine Working Group, 2020: A Report from the Coastal & Marine Working Group of the Maine Climate Council. Maine Climate Council. https://www.maine.gov/future/sites/maine.gov.future/files/inline-files/CoastalMarineWG_FinalStrategyRecommendations_June2020.pdf

130. Dubow, J., D.H. Cornwell, D. Andreasen, A. Staley, K. Tully, K. Gedan, and R. Epanchin-Niell, 2019: Maryland's Plan to Adapt to Saltwater Intrusion and Salinization. Maryland Department of Planning. https://planning.maryland.gov/documents/ourwork/envr-planning/2019-1212-marylands-plan-to-adapt-to-saltwater-intrusion-and-salinization.pdf

131. Besterman, A.F., R.W. Jakuba, W. Ferguson, D. Brennan, J.E. Costa, and L.A. Deegan, 2022: Buying time with runnels: A climate adaptation tool for salt marshes. *Estuaries and Coasts*, **45** (6), 1491–1501. https://doi.org/10.1007/s12237-021-01028-8

132. Maher, N., C. Salazar, and A. Fournier, 2022: Advancing salt marsh restoration for coastal resilience: A learning exchange. *Wetlands Ecology and Management*, **30** (5), 1033–1047. https://doi.org/10.1007/s11273-021-09841-5

133. Neckles, H.A., J.E. Lyons, J.L. Nagel, S.C. Adamowicz, T. Mikula, K.M. O'Brien, B. Benvenuti, and R. Kleinert, 2021: Optimization of Salt Marsh Management at the Rachel Carson National Wildlife Refuge, Maine, Through Use of Structured Decision Making. USGS Open-File Report 2021–1080. U.S. Geological Survey, Reston, VA, 35 pp. https://doi.org/10.3133/ofr20211080

134. Young, S.S., S. Rao, and K. Dorey, 2021: Monitoring the erosion and accretion of a human-built living shoreline with drone technology. *Environmental Challenges*, **5**, 100383. https://doi.org/10.1016/j.envc.2021.100383

135. MDE, 2020: Maryland Ocean Acidification Action Plan 2020. State of Maryland, Maryland Department of the Environment. https://mde.maryland.gov/programs/air/climatechange/mccc/stwg/oa%20action%20plan.pdf

136. Rogers, L.A., R. Griffin, T. Young, E. Fuller, K.S. Martin, and M.L. Pinsky, 2019: Shifting habitats expose fishing communities to risk under climate change. *Nature Climate Change*, **9** (7), 512–516. https://doi.org/10.1038/s41558-019-0503-z

137. Bell, R.J., J. Odell, G. Kirchner, and S. Lomonico, 2020: Actions to promote and achieve climate-ready fisheries: Summary of current practice. *Marine and Coastal Fisheries*, **12** (3), 166–190. https://doi.org/10.1002/mcf2.10112

138. Young, T., E.C. Fuller, M.M. Provost, K.E. Coleman, K. St. Martin, B.J. McCay, and M.L. Pinsky, 2019: Adaptation strategies of coastal fishing communities as species shift poleward. *ICES Journal of Marine Science*, **76** (1), 93–103. https://doi.org/10.1093/icesjms/fsy140

139. Pershing, A., K. Mills, A. Dayton, B. Franklin, and B. Kennedy, 2018: Evidence for adaptation from the 2016 marine heatwave in the Northwest Atlantic Ocean. *Oceanography*, **31** (2), 152–161. https://doi.org/10.5670/oceanog.2018.213

140. Maltby, K.M., S. Kerin, and K.E. Mills, 2023: Barriers and enablers of climate adaptation in fisheries: Insights from Northeast US fishing communities. *Marine Policy*, **147**, 105331. https://doi.org/10.1016/j.marpol.2022.105331

141. NMFS, 2023: Atlantic Large Whale Take Reduction Plan. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://www.fisheries.noaa.gov/new-england-mid-atlantic/marine-mammal-protection/atlantic-large-whale-take-reduction-plan

142. Aaronson, D., D. Hartley, and B. Mazumder, 2021: The effects of the 1930s HOLC "redlining" maps. *American Economic Journal: Economic Policy*, **13** (4), 355–92. https://doi.org/10.1257/pol.20190414

143. Hillier, A.E., 2003: Spatial analysis of historical redlining: A methodological exploration. *Journal of Housing Research*, **14** (1), 137–167. https://www.jstor.org/stable/44944777

144. Krieger, N., G. Van Wye, M. Huynh, P.D. Waterman, G. Maduro, W. Li, R.C. Gwynn, O. Barbot, and M.T. Bassett, 2020: Structural racism, historical redlining, and risk of preterm birth in New York City, 2013–2017. *American Journal of Public Health*, **110** (7), 1046–1053. https://doi.org/10.2105/ajph.2020.305656

145. Rothstein, R., 2017: *The Color of Law: A Forgotten History of How Our Government Segregated America*. Liveright, 368 pp. https://wwnorton.com/books/the-color-of-law/

146. Swope, C.B., D. Hernández, and L.J. Cushing, 2022: The relationship of historical redlining with present-day neighborhood environmental and health outcomes: a scoping review and conceptual model. *Journal of Urban Health*, **99** (6), 959–983. https://doi.org/10.1007/s11524-022-00665-z

147. Renteria, R., S. Grineski, T. Collins, A. Flores, and S. Trego, 2022: Social disparities in neighborhood heat in the northeast United States. *Environmental Research*, **203**, 111805. https://doi.org/10.1016/j.envres.2021.111805

148. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. https://doi.org/10.3390/cli8010012

149. Hsu, A., G. Sheriff, T. Chakraborty, and D. Manya, 2021: Disproportionate exposure to urban heat island intensity across major US cities. *Nature Communications*, **12** (1), 2721. https://doi.org/10.1038/s41467-021-22799-5

150. Mitchell, B.C. and J. Chakraborty, 2018: Exploring the relationship between residential segregation and thermal inequity in 20 U.S. cities. *Local Environment*, **23** (8), 796–813. https://doi.org/10.1080/13549839.2018.1474861

151. Farrell, J., P.B. Burow, K. McConnell, J. Bayham, K. Whyte, and G. Koss, 2021: Effects of land dispossession and forced migration on Indigenous peoples in North America. *Science*, **374** (6567), 4943. https://doi.org/10.1126/science.abe4943

152. Thornbrugh, C., 2021: Testimony on Behalf of the United South and Eastern Tribes before the House Select Committee on the Climate Crisis for the Hearing, "Tribal Voices, Tribal Wisdom: Strategies for the Climate Crisis". United South and Eastern Tribes. https://www.usetinc.org/wp-content/uploads/2021/11/USET-Testimony-Before-House-Select-Committee-on-Climate-Crisis-FINAL-11_16_21-.pdf

153. USET-SPF, 2019: Testimony submitted to the House Natural Resources Subcommittee for Indigenous People of the United States for the Record of the February 12, 2019 Hearing, "The Impacts of Climate Change on Tribal Communities". United South and Eastern Tribes Sovereignty Protection Fund. https://www.usetinc.org/departments/oerm/climate-change/uset-resolutions-reports-and-testimonies-on-climate-change/

154. Zhang, Y., Q. Xiang, Y. Yu, Z. Zhan, K. Hu, and Z. Ding, 2019: Socio-geographic disparity in cardiorespiratory mortality burden attributable to ambient temperature in the United States. *Environmental Science and Pollution Research*, **26**, 694–705. https://doi.org/10.1007/s11356-018-3653-z

155. Siddiqi, S.M., C. Mingoya-LaFortune, R. Chari, B.L. Preston, G. Gahlon, C.C. Hernandez, A. Huttinger, S.R. Stephenson, and J. Madrigano, 2022: The road to Justice40: Organizer and policymaker perspectives on the historical roots of and solutions for environmental justice inequities in U.S. cities. *Environmental Justice*. https://doi.org/10.1089/env.2022.0038

156. Kiaghadi, A. and H.S. Rifai, 2019: Physical, chemical, and microbial quality of floodwaters in Houston following Hurricane Harvey. *Environmental Science & Technology*, **53** (9), 4832–4840. https://doi.org/10.1021/acs.est.9b00792

157. Johnston, J. and L. Cushing, 2020: Chemical exposures, health, and environmental justice in communities living on the fenceline of industry. *Current Environmental Health Reports*, **7**, 48–57. https://doi.org/10.1007/s40572-020-00263-8

158. Declet-Barreto, J. and A.A. Rosenberg, 2022: Environmental justice and power plant emissions in the Regional Greenhouse Gas Initiative states. *PLoS ONE*, **17** (7), e0271026. https://doi.org/10.1371/journal.pone.0271026

159. Wang, Q., M.P. Kwan, J. Fan, and J. Lin, 2021: Racial disparities in energy poverty in the United States. *Renewable and Sustainable Energy Reviews*, **137**, 110620. https://doi.org/10.1016/j.rser.2020.110620

160. Jessel, S., S. Sawyer, and D. Hernández, 2019: Energy, poverty, and health in climate change: A comprehensive review of an emerging literature. *Frontiers in Public Health*, **7**, 357. https://doi.org/10.3389/fpubh.2019.00357

161. Daigle, J.J., N. Michelle, D.J. Ranco, and M.R. Emery, 2019: Traditional lifeways and storytelling: Tools for adaptation and resilience to ecosystem change. *Human Ecology*, **47** (5), 777–784. https://doi.org/10.1007/s10745-019-00113-8

162. Bukvic, A., H. Zhu, R. Lavoie, and A. Becker, 2018: The role of proximity to waterfront in residents' relocation decision-making post-Hurricane Sandy. *Ocean & Coastal Management*, **154**, 8–19. https://doi.org/10.1016/j.ocecoaman.2018.01.002

163. Mach, K.J., C.M. Kraan, M. Hino, A.R. Siders, E.M. Johnston, and C.B. Field, 2019: Managed retreat through voluntary buyouts of flood-prone properties. *Science Advances*, **5** (10), 8995. https://doi.org/10.1126/sciadv.aax8995

164. Siders, A.R., 2019: Social justice implications of US managed retreat buyout programs. *Climatic Change*, **152** (2), 239–257. https://doi.org/10.1007/s10584-018-2272-5

165. Fiack, D., J. Cumberbatch, M. Sutherland, and N. Zerphey, 2021: Sustainable adaptation: Social equity and local climate adaptation planning in U.S. cities. *Cities*, **115**, 103235. https://doi.org/10.1016/j.cities.2021.103235

166. Ebi, K.L., T. Hasegawa, K. Hayes, A. Monaghan, S. Paz, and P. Berry, 2018: Health risks of warming of 1.5 °C, 2 °C, and higher, above pre-industrial temperatures. *Environmental Research Letters*, **13** (6), 063007. https://doi.org/10.1088/1748-9326/aac4bd

167. Finucane, M.L., L.W. May, and J. Chang, 2021: A Scoping Literature Review on Indicators and Metrics for Assessing Racial Equity in Disaster Preparation, Response, and Recovery. RAND Corporation, Santa Monica, CA. https://www.rand.org/pubs/research_reports/RRA1083-1.html

168. McDermott, M., S. Mahanty, and K. Schreckenberg, 2013: Examining equity: A multidimensional framework for assessing equity in payments for ecosystem services. *Environmental Science & Policy*, **33**, 416–427. https://doi.org/10.1016/j.envsci.2012.10.006

169. City of New York, 2019: OneNYC 2050: Building a Strong and Fair City. City of New York, New York, NY. https://www.nyc.gov/site/cpp/our-programs/onenyc.page

170. City of New York, 2017: Local Law 60: Requiring a Study of Environmental Justice Areas and the Establishment of an Environmental Justice Portal. Law number: 2017/060. Committee on Environmental Protection. https://legistar.council.nyc.gov/legislationdetail.aspx?id=1805815&guid=8901a89b-078e-4d47-88d8-ea3e48e715a1

171. City of New York, 2017: Local Law 64: Identifying and Addressing Environmental Justice Issues. Law number: 2017/064. Committee on Environmental Protection. https://legistar.council.nyc.gov/legislationdetail.aspx?id=2460360&guid=0c9f8c9d-5f14-4c1e-b4ad-37bb96f82ba3

172. Leonard, K., 2021: WAMPUM adaptation framework: Eastern coastal Tribal Nations and sea level rise impacts on water security. *Climate and Development*, **13** (9), 842–851. https://doi.org/10.1080/17565529.2020.1862739

173. Hultman, N.E., Clarke, L., , C. Frisch, K. Kennedy, H. McJeon, T. Cyrs, P. Hansel, P. Bodnar, M. Manion, M.R. Edwards, R. Cui, C. Bowman, J. Lund, M.I. Westphal, A. Clapper, J. Jaeger, A. Sen, J. Lou, D. Saha, W. Jaglom, K. Calhoun, K. Igusky, J. deWeese, K. Hammoud, J.C. Altimirano, M. Dennis, C. Henderson, G. Zwicker, and J. O'Neill, 2020: Fusing subnational with national climate action is central to decarbonization: The case of the United States. *Nature Communications*, **11** (1). https://doi.org/10.1038/s41467-020-18903-w

174. Sælen, H., J. Hovi, D. Sprinz, and A. Underdal, 2020: How US withdrawal might influence cooperation under the Paris climate agreement. *Environmental Science & Policy*, **108**, 121–132. https://doi.org/10.1016/j.envsci.2020.03.011

175. Gurney, R.M., A.F. Hamlet, and P.M. Regan, 2021: The influences of power, politics, and climate risk on US subnational climate action. *Environmental Science & Policy*, **116**, 96–113. https://doi.org/10.1016/j.envsci.2020.06.023

176. Dalal, A. and D. Reidmiller, 2023: Status of State-Level Climate Action in the Northeast Region: A Technical Input to the Fifth National Climate Assessment. Gulf of Maine Research Institute, Portland, ME, 9 pp. https://gmri.org/commitments/strategic-initiatives/climate-center/

177. U.S. Climate Alliance, 2022: Inventory of Climate and Clean Energy Policies [Webpage]. http://www.usclimatealliance.org/state-climate-energy-policies

178. GCC, 2022: State Adaptation Progress Tracker. Georgetown University, Georgetown Climate Center. https://www.georgetownclimate.org/adaptation/plans.html

179. U.S. Federal Government, 2022: U.S. Climate Resilience Toolkit: Reports [Webpage]. https://toolkit.climate.gov/reports

180. Yan, J., 2021: The impact of climate policy on fossil fuel consumption: Evidence from the Regional Greenhouse Gas Initiative (RGGI). *Energy Economics*, **100**, 105333. https://doi.org/10.1016/j.eneco.2021.105333

181. Maine DEP, 2022: Ninth Biennial Report on Progress toward Greenhouse Gas Reduction Goals. Maine Department of Environmental Protection. https://www.maine.gov/dep/commissioners-office/kpi/details.html?id=606898

182. RI DEM, 2022: 2019 Rhode Island Greenhouse Gas Emissions Inventory. Rhode Island Department of Environmental Management, 23 pp. https://dem.ri.gov/sites/g/files/xkgbur861/files/2022-12/ridem-ghg-inventory-2019.pdf

183. Molino, G.D., M.A. Kenney, and A.E. Sutton-Grier, 2020: Stakeholder-defined scientific needs for coastal resilience decisions in the northeast U.S. *Marine Policy*, **118**, 103987. https://doi.org/10.1016/j.marpol.2020.103987

184. Powell, E.J., M.C. Tyrrell, A. Milliken, J.M. Tirpak, and M.D. Staudinger, 2019: A review of coastal management approaches to support the integration of ecological and human community planning for climate change. *Journal of Coastal Conservation*, **23** (1), 1–18. https://doi.org/10.1007/s11852-018-0632-y

185. Reckien, D. and E.P. Petkova, 2019: Who is responsible for climate change adaptation? *Environmental Research Letters*, **14** (1), 014010. https://doi.org/10.1088/1748-9326/aaf07a

186. Maine Climate Council, 2022: Maine Climate Council Reports [Webpage]. https://www.maine.gov/future/climate/reports

187. Silka, L., S. Kelemen, and D. Hart, 2020: Assessing the Potential Equity Outcomes of Maine's Climate Action Plan: Framework, Analysis and Recommendations. University of Maine, Senator George J. Mitchell Center for Sustainability Solutions. https://digitalcommons.library.umaine.edu/univ_publications/2273/

188. An Act Driving Clean Energy and Offshore Wind. Bill H.5060, Commonwealth of Massachusetts, July 21, 2022. https://malegislature.gov/bills/192/h5060/billhistory?pagenumber=2

189. An Act Relating to State Affairs and Government—2021 Act on Climate. § 42-6.2, State of Rhode Island, 2021. http://webserver.rilin.state.ri.us/statutes/title42/42-6.2/index.htm

190. An Act Concerning Climate Change Adaptation. Substitute House Bill No. 6441, State of Connecticut, Pub. L. No. 21-115, July 1, 2021. https://www.cga.ct.gov/2021/act/pa/pdf/2021pa-00115-r00hb-06441-pa.pdf

191. Connecticut Insurance Department, 2022: Climate Progress Report. State of Connecticut, Insurance Department. https://portal.ct.gov/-/media/cid/1_reports/2022-climate-progress-report.pdf

192. An Act to Amend the Environmental Conservation Law, the Public Service Law, the Public Authorities Law, the Labor Law and the Community Risk and Resiliency Act, in Relation to Establishing the New York State Climate Leadership and Community Protection Act. S. 6599, A. 8429, State of New York, June 18, 2019. https://legislation.nysenate.gov/pdf/bills/2019/s6599

193. New York State Comptroller, 2021: Progress Report on the New York State Common Retirement Fund's Climate Action Plan. Office of the New York State Comptroller, Albany, NY, 18 pp. https://www.osc.state.ny.us/files/reports/special-topics/pdf/progress-report-climate-action.pdf

194. Herb, J. and L. Auermuller, 2020: A Seat at the Table: Integrating the Needs and Challenges of Underrepresented and Socially Vulnerable Populations into Coastal Hazards Planning in New Jersey. Rutgers, The State University of New Jersey, New Brunswick, NJ. https://njclimateresourcecenter.rutgers.edu/resources/a-seat-at-the-table/

195. Maryland Climate Leadership Academy, 2022: Advancing Maryland's Preparedness, Economic Vitality & Public Health. State of Maryland and the Association of Climate Change Officers. https://www.mdclimateacademy.org/

196. MCC STS, 2020: Scientific Assessment of Climate Change and Its Effects in Maine. Maine Climate Council Scientific and Technical Subcommittee, Augusta, ME. https://www.maine.gov/future/initiatives/climate/climate-council/reports

197. MCC STS, 2021: Maine Climate Science Update 2021. Maine Climate Council Scientific and Technical Subcommittee, Augusta, ME. https://www.maine.gov/future/initiatives/climate/climate-council/reports

198. Maine Climate Council, 2020: Maine Won't Wait: A Four-Year Plan for Climate Action. Maine Climate Council, Coastal and Marine Working Group. https://www.maine.gov/future/initiatives/climate/climate-council/reports

199. An Act to Analyze the Impact of Sea Level Rise. H.P. 1169 - L.D. 1572, State of Maine, June 16, 2021. http://www.mainelegislature.org/legis/bills/getpdf.asp?paper=hp1169&item=4&snum=130

200. An Act To Implement Agency Recommendations Relating to Sea Level Rise and Climate Resilience Provided Pursuant to Resolve 2021, Chapter 67. H.P. 1465 - L.D. 1970, State of Maine, April 12, 2022. https://legislature.maine.gov/legis/bills/getpdf.asp?paper=hp1465&item=3&snum=130

201. An Act to Establish a Pilot Program to Encourage Climate Education in Maine Public Schools. H.P. 1409 - L.D. 1902, State of Maine, May 3, 2022. https://legislature.maine.gov/legis/bills/getpdf.asp?paper=hp1409&item=7&snum=130

202. Lemcke-Stampone, M.D., Cameron P. Wake, and E. Burakowski, 2022: New Hampshire Climate Assessment 2021. University of New Hampshire, Sustainability Institute. https://scholars.unh.edu/sustainability/71

203. NHDES, 2009: The New Hampshire Climate Action Plan: A Plan for New Hampshire's Energy, Environmental and Economic Development Future. New Hampshire Department of Environmental Services. https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/r-ard-09-1.pdf

204. An Act Establishing a Coastal Resilience and Economic Development Program. SB 285-FN, State of New Hampshire, August 5, 2019. https://legiscan.com/nh/text/sb285/id/2033744

205. Galford, G.L., J. Faulkner, L.-A. Dupigny-Giroux, S. Posner, and L. Edling, 2021: The Vermont Climate Assessment 2020. University of Vermont, Gund Institute of Environment, Burlington, VT. https://site.uvm.edu/vtclimateassessment/

206. Vermont Climate Council, 2021: Initial Vermont Climate Action Plan. State of Vermont, Vermont Climate Council. https://climatechange.vermont.gov/sites/climatecouncilsandbox/files/2021-12/Initial%20Climate%20Action%20Plan%20-%20Final%20-%2012-1-21.pdf

207. Vermont Global Warming Solutions Act of 2020. No. 153, State of Vermont, September 22, 2020. https://outside.vermont.gov/agency/anr/climatecouncil/Shared%20Documents/ACT%20153%20As%20Enacted.pdf

208. Commonwealth of Massachusetts, 2022: 2022 Massachusetts Climate Change Assessment, Volume II—Statewide Report. Commonwealth of Massachusetts, Boston, MA. https://www.mass.gov/doc/2022-massachusetts-climate-change-assessment-december-2022-volume-ii-statewide-report/download

209. Massachusetts EEA, 2022: Massachusetts Clean Energy and Climate Plan for 2025 and 2030. Commonwealth of Massachusetts, Executive Office of Energy and Environmental Affairs. https://www.mass.gov/info-details/massachusetts-clean-energy-and-climate-plan-for-2025-and-2030

210. An Act Creating a Next-Generation Roadmap for Massachusetts Climate Policy. Bill S.9, Commonwealth of Massachusetts, January 19, 2021. https://malegislature.gov/bills/192/s9

211. State of Rhode Island, 2018: Resilient Rhody: The Statewide Climate Resilience Action Strategy. State of Rhode Island, 85 pp. https://climatechange.ri.gov/sites/g/files/xkgbur481/files/documents/resilientrhody18.pdf

212. RI EC4, 2022: Rhode Island 2022 Climate Update. State of Rhode Island, Rhode Island Executive Climate Change Coordinating Council. https://climatechange.ri.gov/act-climate/2022-climate-update

213. CIRCA, 2019: Connecticut Physical Climate Science Assessment Report: Observed Trends and Projections of Temperature and Precipitation. Connecticut Institute for Resilience and Climate Adaptation, 74 pp. https://circa.uconn.edu/ct-climate-science/

214. GC3, 2021: Taking Action on Climate Change and Building a More Resilient Connecticut for All. Phase 1 Report: Near-Term Actions. Governor's Council on Climate Change, 56 pp. https://portal.ct.gov/-/media/deep/climatechange/gc3/gc3_phase1_report_jan2021.pdf

215. An Act Concerning Provisions Related to Revenue and Other Items to Implement the State Budget for the Biennium Ending June 30, 2023. Senate Bill No. 1202, State of Connecticut, Pub. L. No. 21-2, July 1, 2021. https://www.cga.ct.gov/2021/act/pa/pdf/2021pa-00002-r00sb-01202ss1-pa.pdf

216. NYSDEC, 2021: Observed and Projected Climate Change in New York State: An Overview. New York State Department of Environmental Conservation. https://www.dec.ny.gov/docs/administration_pdf/ccnys2021.pdf

217. New York State Climate Action Council, 2021: New York State Climate Action Council Draft Scoping Plan. State of New York. https://climate.ny.gov/Resources/Draft-Scoping-Plan

218. New York State Climate Action Council, 2022: New York State Climate Action Council Scoping Plan. State of New York. https://climate.ny.gov/resources/scoping-plan/

219. An Act to Amend the Agriculture and Markets Law and the Soil and Water Conservation Districts Law, in Relation to Establishing the Soil Health and Climate Resiliency Act. A5386A, State of New York, February 16, 2021. https://www.nysenate.gov/legislation/bills/2021/a5386

220. An Act to Amend the Economic Development Law, in Relation to Allowing for Eligibility of Green Chips Projects in the Excelsior Tax Credit Program. S9467, State of New York, May 31, 2022. https://www.nysenate.gov/legislation/bills/2021/s9467

221. Clean Water, Clean Air and Green Jobs Environmental Bond Act. S8008C, State of New York, January 19, 2022. https://www.nysenate.gov/legislation/bills/2021/S8008

222. PADEP, 2021: Pennsylvania Climate Impacts Assessment. Pennsylvania Department of Environmental Protection. https://www.dep.pa.gov/Citizens/climate/Pages/impacts.aspx

223. PADEP, 2021: Pennsylvania Climate Action Plan. Pennsylvania Department of Environmental Protection. https://www.dep.pa.gov/citizens/climate/pages/pa-climate-action-plan.aspx

224. Kopp, R.E., C.J. Andrews, A. Broccoli, A. Garner, D. Kreeger, R. Leichenko, N. Lin, C.M. Little, J.A. Miller, J.K. Miller, K. Miller, R. Moss, P. Orton, A. Parris, D.A. Robinson, W. Sweet, J. Walker, C.P. Weaver, K. White, M. Campo, M.B. Kaplan, J. Herb, and L. Auermuller, 2019: New Jersey's Rising Seas and Changing Coastal Storms: Report of the 2019 Science and Technical Advisory Panel. Rutgers, The State University of New Jersey. https://doi.org/10.7282/t3-eeqr-mq48

225. NJDEP, 2020: 2020 New Jersey Scientific Report on Climate Change. Version 1, Hill, R., M.M. Rutkowski, L.A. Lester, H. Genievich, and N.A. Procopio, Eds. New Jersey Department of Environmental Protection, Trenton, NJ, 184 pp. https://dep.nj.gov/wp-content/uploads/climatechange/nj-scientific-report-2020.pdf

226. NJDEP, 2022: Climate Change Impacts on Human Health and Communities. New Jersey Department of Environmental Protection. https://dep.nj.gov/wp-content/uploads/climatechange/nj-scientific-report-human-health-addendum.pdf

227. Angarone, N., T. Caggiano, R. Hill, and J. Jahre, 2021: State of New Jersey Climate Change Resilience Strategy. State of New Jersey, New Jersey Interagency Council on Climate Resilience. https://dep.nj.gov/wp-content/uploads/climatechange/nj-climate-resilience-strategy-2021.pdf

228. State of New Jersey, 2019: 2019 New Jersey Energy Master Plan—Pathway to 2050. State of New Jersey, 290 pp. https://nj.gov/emp/docs/pdf/2020_NJBPU_EMP.pdf

229. NJDEP, 2020: New Jersey's Global Warming Response Act 80x50 Report. New Jersey Department of Environmental Protection. https://dep.nj.gov/wp-content/uploads/climatechange/nj-gwra-80x50-report-2020.pdf

230. An Act Concerning the Reduction of Greenhouse Gases. Bill S3207 SaSa (2R), State of New Jersey, 2019. https://www.njleg.state.nj.us/bill-search/2018/s3207

231. An Act Requiring New Jersey to Join the U.S. Climate Alliance and Uphold the Paris Climate Accord. NJ S598, State of New Jersey, February 21, 2018. https://legiscan.com/nj/bill/s598/2018

232. Industrial Economics, 2022: An Economic Analysis of the Impacts of Climate Change in the State of Delaware. Prepared for the Delaware Department of Natural Resources and Environmental Control. Industrial Economics, Incorporated, Cambridge, MA. https://documents.dnrec.delaware.gov/energy/Documents/Climate/Plan/Economic-Analysis-of-the-Impacts-of-Climate-Change-in-the-State-of-Delaware.pdf

233. de Mooy, J., M. Pletta, and I. Yue, 2021: Delaware's Climate Action Plan. Delaware Department of Natural Resources and Environmental Control, Dover, DE. https://dnrec.alpha.delaware.gov/climate-plan/

234. An Act to Amend Title 26 of the Delaware Code Relating to Renewable Energy Portfolio Standards. Senate Bill No. 33, State of Delaware, February 10, 2021. https://legis.delaware.gov/billdetail?legislationid=48278

235. Boesch, D.F., W.C. Boicourt, R.I. Cullather, T. Ezer, G.E. Galloway Jr., Z.P. Johnson, K.H. Kilbourne, M.L. Kirwan, R.E. Kopp, S. Land, M. Li, W. Nardin, C.K. Sommerfield, and W.V. Sweet, 2018: Sea-Level Rise: Projections for Maryland 2018. University of Maryland, Center for Environmental Science, Cambridge, MD, 27 pp. https://mde.maryland.gov/programs/air/climatechange/mccc/documents/sea-levelriseprojectionsmaryland2018.pdf

236. MDE, 2021: The Greenhouse Gas Emissions Reduction Act: 2030 GGRA Plan. Maryland Department of the Environment. https://mde.maryland.gov/programs/Air/ClimateChange/Documents/2030%20GGRA%20Plan/THE%202030%20GGRA%20PLAN.pdf

237. Maryland Commission on Climate Change, 2021: Annual Report and Building Energy Transition Plan. Maryland Commission on Climate Change, 29 pp. https://mde.maryland.gov/programs/air/ClimateChange/MCCC/Documents/2021%20Annual%20Report%20FINAL%20(2).pdf

238. Climate Solutions Now Act of 2022. SB 528, State of Maryland, June 1, 2022. https://mgaleg.maryland.gov/2022rs/fnotes/bil_0008/sb0528.pdf

239. An Act Concerning Sea Level Rise Inundation and Coastal Flooding—Construction, Adaptation, and Mitigation. HB1350 - CH0628, State of Maryland, July 1, 2018. https://mgaleg.maryland.gov/mgawebsite/legislation/details/hb1350?ys=2018rs

240. City of Washington DC, 2016: Vulnerability and Risk Assessment: Climate Change Adaptation Plan for the District of Columbia. City of Washington, DC. https://doee.dc.gov/sites/default/files/dc/sites/ddoe/publication/attachments/AREA_Vulnerability_Assessment_DRAFT_2016-06-21lowres_.pdf

241. City of Washington DC, 2018: Clean Energy DC: The District of Columbia Climate and Energy Action Plan. U.S. Department of Energy and Environment. https://doee.dc.gov/cleanenergydc

242. City of Washington DC, 2018: Sustainable DC 2.0 Plan. U.S. Department of Energy and Environment. https://sustainable.dc.gov/sdc2

243. City of Washington DC, 2019: Resilient DC: A Strategy to Thrive in the Face of Change. City of Washington, DC. https://resilient.dc.gov/

244. City of Washington DC, 2020: Climate Resilient by 2050: Making Progress Towards a Climate Ready DC. U.S. Department of Energy and Environment. https://doee.dc.gov/climateready

245. Saint Regis Mohawk Tribe, 2013: Climate Change Adaptation Plan for Akwesasne. Saint Regis Mohawk Tribe. https://dvc479a3doke3.cloudfront.net/_uploads/site_files/ClimateChange.pdf

246. Mi'kmaq Nation, 2022: Thirteen Moons: Climate Change Adaptation Plan. Mi'kmaq Nation. https://www.usetinc.org/departments/oerm/climate-change/tribal-climate-planning-documents/

247. City of Boston, 2019: 2019 Climate Action Plan Update. City of Boston. https://www.boston.gov/sites/default/files/embed/file/2019-10/city_of_boston_2019_climate_action_plan_update_4.pdf

248. City of Philadelphia, 2021: Philadelphia Climate Action Playbook. City of Philadelphia, Greenworks Philadelphia. https://www.phila.gov/media/20210113125627/Philadelphia-Climate-Action-Playbook.pdf

249. Cities of Portland and South Portland, 2019: One Climate Future: Climate Change Vulnerability Assessment. Portland and South Portland Sustainability Offices. https://www.oneclimatefuture.org/wp-content/uploads/2020/12/OneClimateFuture_VulnerabilityAssessment_Final.pdf

250. Cities of Portland and South Portland, 2020: Our Contributions to Climate Change: GHG Emissions. Portland and South Portland Sustainability Offices. https://www.oneclimatefuture.org/wp-content/uploads/2021/02/Emissions_Downsized_Web.pdf

251. Cities of Portland and South Portland, 2021: One Climate Future: Charting a Course for Portland and South Portland. Portland and South Portland Sustainability Offices. https://www.oneclimatefuture.org/wp-content/uploads/2021/02/OneClimateFuture_FinalJan2021_Downsized.pdf

252. City of Pittsburgh, 2017: Executive Order 2017-08: Reinforcing Pittsburgh's Commitment to the Global Partnership on Climate Change. City of Pittsburgh, Office of the Mayor, Pittsburgh, PA. 3 pp. https://apps.pittsburghpa.gov/mayorpeduto/Climate_exec_order_06.02.17_(1).pdf

253. City of Pittsburgh, 2021: Earth Day Executive Order. City of Pittsburgh, Office of the Mayor, 5 pp. https://apps.pittsburghpa.gov/redtail/images/14057_FINAL_Climate_Change_Earth_Day_Executive_Order.pdf

254. City of Pittsburgh, 2008: Pittsburgh Climate Action Plan Version 1.0. City of Pittsburgh, Green Building Alliance, Pittsburgh, PA. https://www.yumpu.com/en/document/view/22813674/2008-pittsburgh-climate-action-plan-city-of-pittsburgh

255. City of Pittsburgh, 2017: Climate Action Plan: Version 3.0. City of Pittsburgh, Pittsburgh's Green Government Task Force, Pittsburgh, PA. https://apps.pittsburghpa.gov/redtail/images/7101_Pittsburgh_Climate_Action_Plan_3.0.pdf

256. City of Pittsburgh, 2018: Pittsburgh Equity Indicators: A Baseline Measurement for Enhancing Equity in Pittsburgh. Annual Report: 2018. City of Pittsburgh, Office of the Mayor. https://pittsburghpa.gov/equityindicators/documents/PGH_Equity_Indicators_2018.pdf

257. City of Pittsburgh, 2021: State of Sustainability 2019-2020. City of Pittsburgh, Department of City Planning Sustainability and Resilience Division, 8 pp. https://apps.pittsburghpa.gov/redtail/images/14821_State_of_Sustainability_2020_Final.pdf

258. City of Pittsburgh, 2022: Pittsburgh Zoning Code, Title Thirteen: City of Pittsburgh Stormwater Management Ordinance. Pittsburgh, PA. https://library.municode.com/pa/pittsburgh/codes/code_of_ordinances?nodeId=PIZOCO_TITTHIRTEENSTMA

259. City of Morgantown, 2022: Green Team. City of Morgantown, Morgantown, WV. http://www.morgantownwv.gov/295/green-team

260. Morgantown Municipal Green Team, 2020: Annual Report 2019. City of Morgantown, Morgantown, WV. http://www.morgantownwv.gov/documentcenter/view/3184/green-team-2019-annual-report

261. Morgantown Municipal Green Team, 2018: Strategic Plan (2018–2022). City of Morgantown, Morgantown, WV. http://www.morgantownwv.gov/documentcenter/view/1862/morgantown-green-team-strategic-plan-2018-2022

262. City of Morgantown, 2022: Money, Energy, and Sustainability. City of Morgantown. http://www.morgantownwv.gov/documentcenter/view/1866/morgantown-energy-policy-guide

263. Bernhardt, A., C. Kousky, A. Read, and C. Sykes, 2021: Community-Based Catastrophe Insurance: A Model for Closing the Disaster Protection Gap. Marsh and McLennan Companies, Inc., 33 pp. https://www.marshmclennan.com/insights/publications/2021/february/community-based-catastrophe-insurance.html

264. Buchner, B., B. Naran, P. Fernandes, R. Padmanabhi, P. Rosane, M. Solomon, S. Stout, C. Strinati, R. Tolentino, G. Wakaba, Y. Zhu, C. Meattle, and S. Guzmán, 2021: Global Landscape of Climate Finance 2021. Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2021/

265. Tall, A., S. Lynagh, C.B. Vecchi, P. Bardouille, F.M. Pino, E. Shabahat, V. Stenek, F. Stewart, S. Power, C. Paladines, P. Neves, and L. Kerr, 2021: Enabling Private Investment in Climate Adaptation & Resilience. World Bank Group and Global Facility for Disaster Reduction and Recovery. https://openknowledge.worldbank.org/entities/publication/6219bf23-87e1-5f30-aaf9-30e0cd793ce3

266. Hyman, E., 2022: Introduction to Financing Climate Change Mitigation and Adaptation. U.S. Agency for International Development, Washington, DC. https://www.climatelinks.org/sites/default/files/asset/document/2022-12/Introduction%20to%20Financing%20Climate%20Change%20Mitigation%20and%20Adaptation%20_0.pdf

267. Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372** (6549), 8054. https://doi.org/10.1126/science.abc8054

268. EPA, 2023: Federal Funding and Technical Assistance for Climate Adaptation. U.S. Environmental Protection Agency. https://www.epa.gov/arc-x/federal-funding-and-technical-assistance-climate-adaptation

269. Insurance Information Institute, 2018: How Insurance Drives Economic Growth. Insurance Information Institute, 18 pp. https://www.iii.org/sites/default/files/docs/pdf/insurance-driver-econ-growth-053018.pdf

270. AON, 2022: 2021 Weather, Climate and Catastrophe Insight. AON. https://www.aon.com/reinsurance/getmedia/1b516e4d-c5fa-4086-9393-5e6afb0eeded/20220125-2021-weather-climate-catastrophe-insight.pdf

271. Insurance Information Institute, 2022: Facts + Statistics: U.S. Catastrophes [Webpage]. https://www.iii.org/fact-statistic/facts-statistics-us-catastrophes

272. Insurance Information Institute, 2022: Spotlight on: Flood Insurance [Webpage]. https://www.iii.org/article/spotlight-on-flood-insurance

273. Kunreuther, H., S. Wachter, C. Kousky, and M. Lacour-Little, 2018: Flood Risk and the U.S. Housing Market. University of Pennsylvania, The Wharton School, 38 pp. https://penniur.upenn.edu/uploads/media/Flood_Risk_and_the_US_Housing_Market.pdf

274. Klotzbach, P.J., S.G. Bowen, R. Pielke, and M. Bell, 2018: Continental U.S. hurricane landfall frequency and associated damage: Observations and future risks. *Bulletin of the American Meteorological Society*, **99** (7), 1359–1376. https://doi.org/10.1175/bams-d-17-0184.1

275. GAO, 2021: FEMA Flood Maps: Better Planning and Analysis Needed to Address Current and Future Flood Hazards. GAO-22-104079. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-22-104079.pdf

276. Netusil, N.R., C. Kousky, S. Neupane, W. Daniel, and H. Kunreuther, 2021: The willingness to pay for flood insurance. *Land Economics*, **97** (1), 17–38. https://doi.org/10.3368/wple.97.1.110819-0160r1

277. FEMA, 2022: Flood Insurance Manual. Risk Rating 2.0: Equity in Action Edition. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_nfip-flood-insurance-manual-sections-1-6_102022.pdf

278. NAR, 2023: Single-Family Existing-Home Sales and Prices, February 2023. National Association of Realtors. https://www.nar.realtor/newsroom/existing-home-sales-surged-14-5-in-february-ending-12-month-streak-of-declines

279. Michel-Kerjan, E., S. Lemoyne de Forges, and H. Kunreuther, 2012: Policy tenure under the U.S. National Flood Insurance Program (NFIP). *Risk Analysis*, **32** (4), 644–658. https://doi.org/10.1111/j.1539-6924.2011.01671.x

280. CRS, 2022: Introduction to the National Flood Insurance Program (NFIP). CRS Report R44593. Congressional Research Service. https://sgp.fas.org/crs/homesec/R44593.pdf

281. FEMA, 2021: Risk Rating 2.0 Is Equity in Action. U.S. Department of Homeland Security, Federal Emergency Management Agency, 6 pp. https://www.fema.gov/sites/default/files/documents/fema_rr-2.0-equity-action_0.pdf

282. FEMA, 2022: National Flood Insurance Program's Reinsurance Program. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/flood-insurance/work-with-nfip/reinsurance

283. Frank, T., 2019: The private sector is returning to the flood insurance game. *E&E News via Scientific American*. https://www.scientificamerican.com/article/the-private-sector-is-returning-to-the-flood-insurance-game/

284. Chaudhury, A., 2020: Role of intermediaries in shaping climate finance in developing countries—Lessons from the Green Climate Fund. *Sustainability*, **12** (14), 5507. https://doi.org/10.3390/su12145507

285. CBO, 2020: Public-Private Partnerships for Transportation and Water Infrastructure. Congressional Budget Office. https://www.cbo.gov/publication/56044

286. USAFacts, 2021: What Does America Spend on Transportation and Infrastructure? Is Transportation Infrastructure Improving? USAFacts. https://usafacts.org/state-of-the-union/transportation-infrastructure/

287. ASCE, 2021: A Comprehensive Assessment of America's Infrastructure: 2021 Report Card for America's Infrastructure. American Society of Civil Engineers. https://infrastructurereportcard.org/

288. The White House, 2021: Fact sheet: The bipartisan infrastructure deal. The White House, Washington, DC, November 6, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/

289. Levitt, J.N. and C. Navalkha, 2022: From the Ground Up: How Land Trusts and Conservancies Are Providing Solutions to Climate Change. Watts, L.A. and A. Finch, Eds. Lincoln Institute of Land and Policy. https://www.lincolninst.edu/sites/default/files/pubfiles/from-the-ground-up-full.pdf

290. Buffalo Sewer Authority, 2019: Rain Check 2.0 Opportunity Report: The Next Generation of Green Infrastructure in Buffalo. City of Buffalo, Buffalo Sewer Authority. https://raincheckbuffalo.org/app/uploads/2019/05/190515-RC2-OpportunityReport_sml.pdf

291. Friedland, K.D., J.A. Langan, S.I. Large, R.L. Selden, J.S. Link, R.A. Watson, and J.S. Collie, 2020: Changes in higher trophic level productivity, diversity and niche space in a rapidly warming continental shelf ecosystem. *Science of The Total Environment*, **704**, 135270. https://doi.org/10.1016/j.scitotenv.2019.135270

292. Huang, H., J.M. Winter, E.C. Osterberg, R.M. Horton, and B. Beckage, 2017: Total and extreme precipitation changes over the northeastern United States. *Journal of Hydrometeorology*, **18 (6)**, 1783–1798. https://doi.org/10.1175/JHM-D-16-0195

Fifth National Climate Assessment: Chapter 22

# Southeast

# Chapter 22. Southeast

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# Introduction

Patterns of climate risk, social vulnerability, and climate adaptation in the Southeast echo centuries of human history. The region consists of highly diverse communities and landscapes, including one of the most biodiverse areas in the continental United States. The Southeast's ecosystems, stewarded for generations by Indigenous Peoples, are now in a precarious state. Centuries of political and land-use decisions have threatened the landscape and the people, with a few prospering at the expense of many. These decisions, shaped by a long history of systemic and structural racial discrimination and aggression, continue to have lasting harmful effects on the preparedness of Southeast communities for mounting climate change threats. The institutions of slavery and intergenerational ownership of individuals as property, Jim Crow segregation, and housing discrimination have resulted in many BIPOC (Black, Indigenous, and People of Color) communities living in neighborhoods that are disproportionately exposed to environmental risks and with fewer resources to address them when compared to majority White communities (Figure 32.18).[1,2,3,4,5,6,7,8,9,10,11,12,13] Furthermore, these frontline communities—those with higher exposures, greater vulnerability, and less adaptive capacity to climate change impacts—continue to face forms of discrimination that increase their vulnerability to climate risks and reduce their options for resilience (Figure 20.1).[1,14,15] These inequities are further complicated by the Southeast's population changes, economic investments, and rising tax revenues in urban and suburban areas. Wealthier communities are able to seek out external resources needed to implement innovative climate resilience and adaptation projects.[16,17] Meanwhile, smaller and more rural communities often lack the capacity to receive and spend funding, train leadership, and advocate for climate adaptation planning.[18]

With virtually no exceptions, climate change in the Southeast continues to exhibit the trends that were reported in the last National Climate Assessment (NCA).[19] We now better understand the increasing intensity of climate stressors in the Southeast, including extreme heat, extreme precipitation events, drought persistence and strength, sea level change, and tropical cyclones (Table A4.1), as well as decreases in the intensity and frequency of disruptive cold-season events like snowfall and frost days (Ch. 2).[20]

There have been notable advancements in Southeast climate change adaptation in recent years.[19] For example, adaptation plans created by Tribal Nations have contributed to those Nations' cultural continuance in a changing climate—that is, their "capacity to maintain members' cultural integrity, health, economic vitality, and political order into the future and avoid having members experience preventable harms" (KM 16.3).[21,22] Indigenous stewardship continues in the Southeast in many contemporary Indigenous "cultural landscapes," or places where Tribal members have centuries-old connections (Box 22.3). In these places, members continue cultivating cultural practices including hunting, fishing, foraging, and ceremony.[23] The increasing hazards of climate change, pollution, and threats to land and water rights–which may be underestimated by existing environmental justice analyses[24,25]–put a strain on Indigenous Peoples' sovereignty and their ability to have high levels of cultural continuance.[21,22,26]

Moreover, communities throughout the Southeast are exploring how to spur action through communicating about climate change science across both formal (classroom) and informal (outside of classrooms) learning,[27,28,29,30,31,32,33] setting clear climate goals,[34] and responding to the mounting threats and stressors that climate change presents (Figure 31.1).[35] However, there has been an equal, if not a greater, number of failures to adequately prepare the region's homeplaces, infrastructure, economy, and livelihoods for the threats of a warming climate, seen in the poorly coordinated responses to hurricanes over many years, from Hurricanes Katrina[36] to Florence[37] and Ida,[38] especially for frontline communities.[39] Moreover, uncoordinated adaptation efforts across municipal and state boundaries to address climate change may hinder the long-term efficacy of any individual project while delaying the shared goal of securing the vitality of the Southeast.

## Key Message 22.1

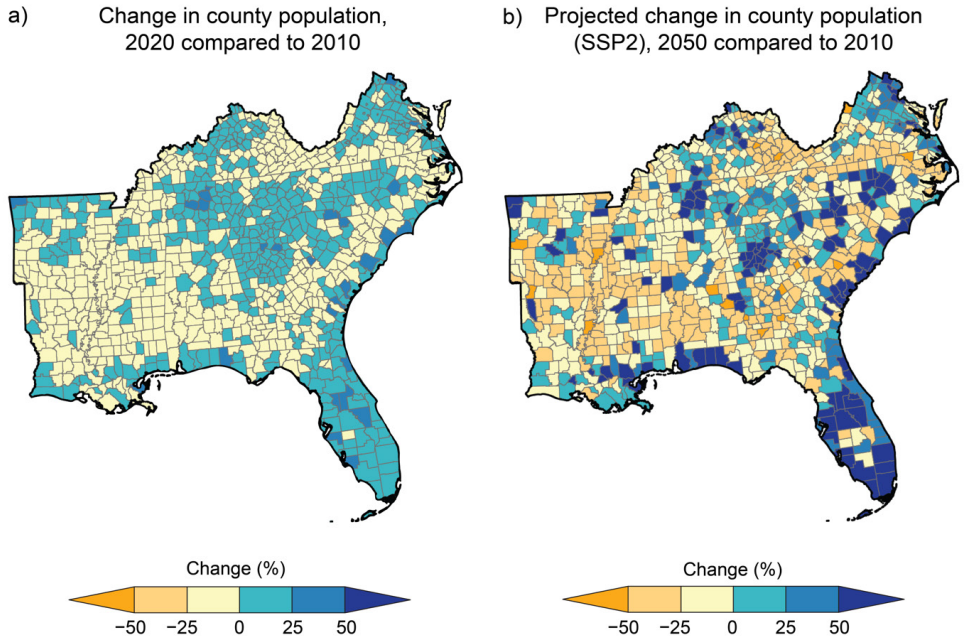
## Regional Growth Increases Climate Risks

The Southeast's population has grown and is expected to continue growing, mostly in metropolitan areas and along its coastline (*very likely*, *very high confidence*), putting more communities and their assets into harm's way from increasing risks related to climate and land-use changes (*very likely*, *very high confidence*). Conversely, many rural places are facing declining populations with a growing percentage of older residents (*very high confidence*), making these areas particularly vulnerable to the impacts of a changing climate (*likely*, *high confidence*). At the same time, decision-makers frequently use outdated and/or limited information on climate-related risks to inform adaptation plans, which as a result fail to account for worsening future conditions (*likely*, *high confidence*). These climate adaptation efforts also tend to be concentrated in wealthier communities, leaving under-resourced and more rural populations, communities of color, and Tribal Nations at growing and disproportionate risk (*likely, high confidence*).

### *A Growing Region Means Increased Climate Risks*

All but one of the Southeast's states—Mississippi—experienced population growth over the last decade, and most of the fastest-growing large US cities are located in the region.[40] Even under scenarios with moderate population growth (e.g., Shared Socioeconomic Pathway [SSP] 2), the region's population is expected to increase (Figure 22.1).[41]

**Population Change in the Southeast**

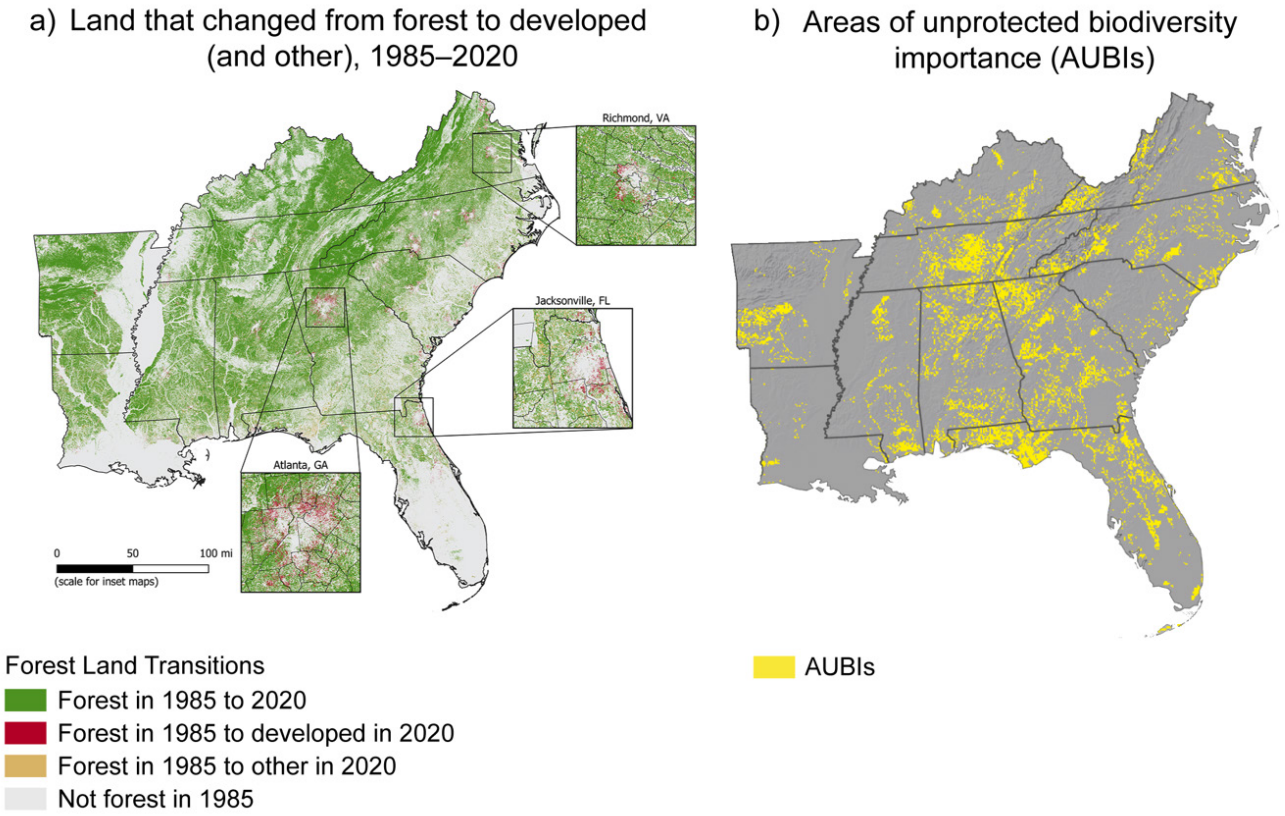



**Population change in the Southeast exposes more people to climate threats along the coast and in cities while leaving rural areas with limited capacity.**

**Figure 22.1.** (**a**) Between 2010 and 2020, unequal population change occurred in the Southeast, with coastal and metropolitan counties growing while many rural counties' populations declined. (**b**) This pattern is expected to continue through 2050 (under SSP2) and will expose more people to climate threats. Diminishing populations reduce the capacity of rural counties to adapt to climate threats by reducing critical financial and social resources, such as tax bases and community care organizations. Figure credit: Groundwork USA, NOAA NCEI, and CISESS NC.

Southeast land cover equal to about 1.7 million football fields changed from forested to developed between 1985 and 2019, more than in any other NCA region (Figure 22.2a; Ch. 6). Urbanized land cover is estimated to increase by more than 9% throughout the region by 2060, based on urban area growth trends during 1990–2010,[42] further threatening the region's unique terrestrial and aquatic biodiversity (Figure 22.2b; KM 8.1).

## Land-Cover Change and Biodiversity

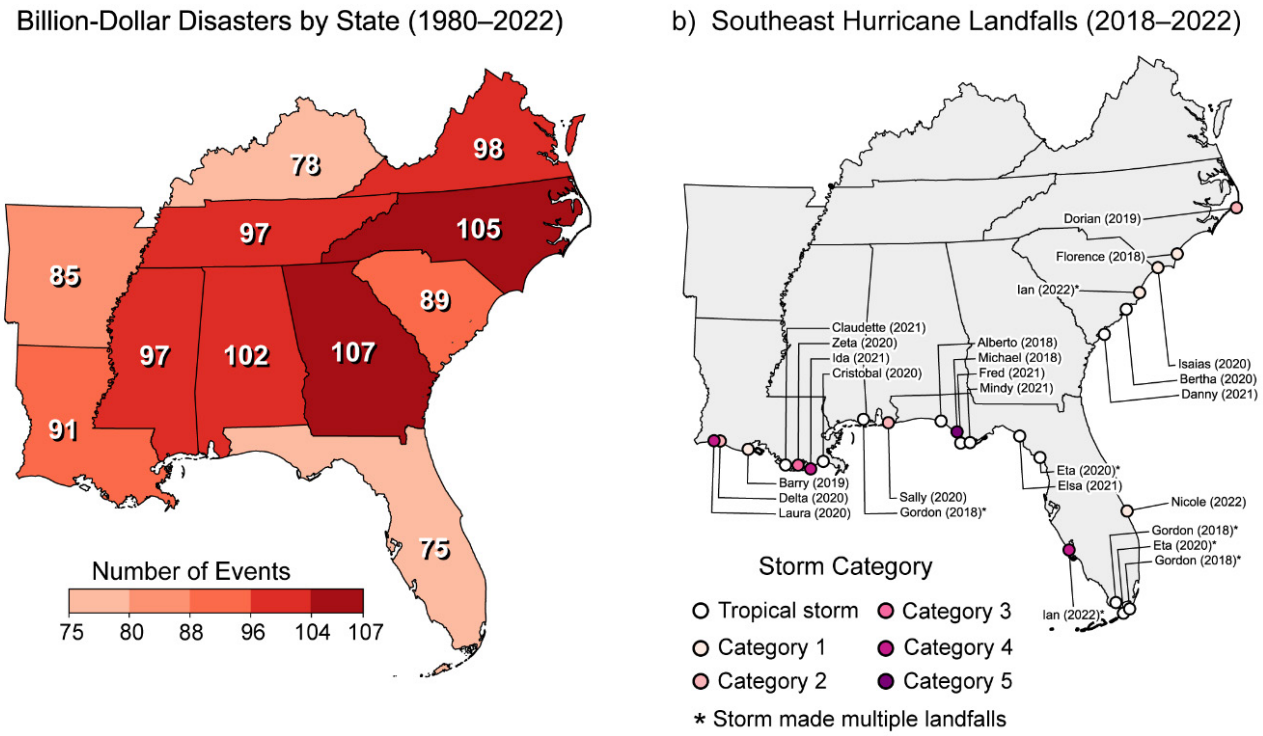



**Land cover change and sprawling development threaten unprotected biodiversity hotspots in the Southeast.**

**Figure 22.2.** (**a**) The Southeast has lost more forested area to development and other land uses (cropland, grass/shrub, and water) than any other National Climate Assessment region since 1985. (**b**) Many of the region's most biodiverse landscapes remain unprotected, threatening unique species of birds, fish, and amphibians. Future sprawl may threaten these landscapes, known as Areas of Unprotected Biodiversity Importance (AUBIs). Figure credits: (a) Groundwork USA, Oak Ridge National Laboratory, NOAA NCEI, and CISESS NC; (b) adapted with permission from Hamilton et al. 2022.[43]

Unconstrained exurban and suburban sprawl will further expose human development to weather- and climate-related risks such as wildfire,[44] hurricanes,[45] floods,[13,46] intensifying thunderstorms,[47] and tornadoes.[48] Growth along the region's coastlines[49] has increased the population exposed to coastal-specific climate threats.[13,50,51,52,53] Although the Southeast has historically experienced more billion-dollar disaster events than the rest of the country[54] and has weathered multiple hurricanes since 2018 (Figure 22.3), there is considerable regional variation among residents' perceptions of whether climate change will personally harm them.[55,56]

## Billion-Dollar Disasters and Hurricanes in the Southeast




**The Southeast frequently experiences costly weather-related disasters, which are worsened by climate change.**

**Figure 22.3.** (**a**) The map shows NOAA billion-dollar disasters by state during 1980–2022 in the Southeast. The map adds up billion-dollar events for each state affected (i.e., it does not mean that each state shown suffered at least $1 billion in losses for each event). (**b**) The map shows Southeast hurricane landfalls during 2018–2022. Since 1980, the Southeast has had a higher frequency of billion-dollar disasters than other National Climate Assessment regions. Disasters attributed to hurricanes have been particularly damaging. Hurricane impacts can spread far inland and even outside the region, including major flooding, which is not captured in the Saffir–Simpson Scale depicting hurricane landfall intensity (b). Because map (b) is limited to 2018–2022, it excludes prior billion-dollar hurricanes that hit the Southeast, including Hugo (1989), Andrew (1992), Fran (1996), Floyd (1999), Charley (2004), Rita (2005), Katrina (2005), Matthew (2016), and Irma (2017). Figure credit: Mississippi State University.

Some of the Southeast's growth follows patterns of urban renewal, with affluent and young people returning to urban areas and displacing under-resourced communities to suburban and rural areas.[57] As a result of this displacement and long-standing underinvestment, under-resourced communities face more environmental hazards and increasing risks (Figure 22.4b)[3,13] but have less access to climate-ready infrastructure such as housing (Figure 22.4a), dwellings with strong building codes[58] that minimize disruption during storms,[59,60] public transit,[61] community resource centers for heat and cold relief,[62] and up-to-date stormwater management systems.[63] These communities often also lack a well-resourced local and/or state governmental workforce[64] to analyze, plan for, and mitigate risks (KM 20.1).[16,17,18,65,66]

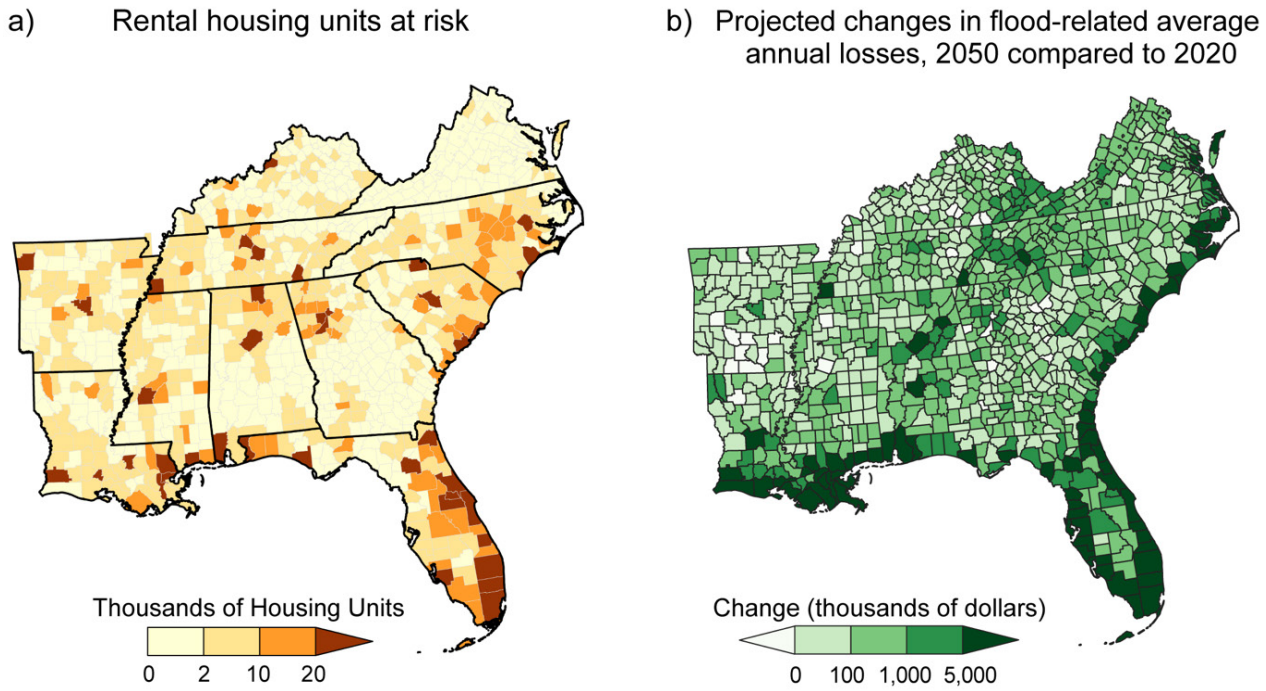
## *Inland and Coastal Flooding Threatens the Present and Future*

Southeast flood risk is inequitably distributed due to both climate and non-climate stressors. Physical stressors such as increases in rainfall, temperatures, and sea level, in addition to land cover change, exacerbate flood risks (KM 4.2),[13,50,67,68] while social and economic policies, including institutional investments and disinvestments, differentially shape risk, vulnerability, and exposure to flooding.[69,70,71] Compounding

preexisting social and economic disparities are changes in precipitation patterns. For instance, shifting autumn precipitation patterns have been attributed to human-caused climate change,[72] and some Southeast counties with higher social vulnerability are experiencing more frequent flooding.[73]

Mandatory flood risk disclosure requirements largely depend on state-by-state policies,[74] and virtually all requirements apply only to home sales. Millions of rental housing units in the region are within counties that have high Expected Annual Loss ratings from FEMA,[75] and confidence is growing that areas currently populated by communities of color, who also are more often renters, will face disproportionately high future flood risks (Figure 22.4).[3,13] Furthermore, other forms of housing that are vulnerable to climate risks include mobile homes and manufactured housing, which are concentrated in the Southeast.[40,76,77] These populations tend to face more barriers to accessing flood insurance and federal flood disaster assistance and more often experience adverse outcomes during disaster recovery, due in part to the lack of disaster relief programs for renters and the rising cost of flood insurance.[78,79,80] Additionally, the potential overvaluation of coastal residential housing stock makes it even more challenging to move people out of harm's way due to the upper limits placed on the amount of compensation these programs can offer and peoples' reluctance to sell these properties and lose rental revenue. For example, in Miami-Dade County, Florida, the total overvaluation of properties is $3.9 billion, and in nearby Duval County, where Jacksonville is the county seat (Figure 22.5), overvaluation exceeds $420 million.[81] Across the Southeast, the average total overvaluation of properties is estimated to be around $110 million per county. Florida has the highest statewide total average overvaluation at $749 million, while Mississippi has an undervaluation of $20 million.[81]

## Current and Projected Risks to Homes




**Vulnerable homes in the Southeast will face increasing climate threats in the future.**

**Figure 22.4.** (**a**) Thousands of rental housing units across the Southeast are located in counties with at least a "relatively moderate" Expected Annual Loss score in FEMA's National Risk Index. (**b**) Projected future increases to flood-related average annual losses by 2050 compared to 2020 under an intermediate scenario (RCP4.5) disproportionately affect under-resourced populations and communities of color and are amplified by population growth, exposing more people to increased flood risk. (a) Adapted with permission from Harvard Joint Center for Housing Studies, America's Rental Housing, © 2022 by the President and Fellows of Harvard College, www.jchs.harvard.edu. All rights reserved;[75] (b) adapted from Wing et al. 2022[13] [CC BY 4.0].

Flooding impacts infrastructure and, in turn, public health. Injury, illness, and death can result from exposure to mold from floodwater damage,[82,83] onsite wastewater treatment system failures,[84] and carbon monoxide poisoning from misuse of generators for emergency power.[85,86,87] In addition, healthcare facilities may be damaged by flooding or unable to handle an influx of demand.[88,89] Damage to roads and bridges might prevent access to these facilities, disrupt the supply of medications and equipment,[90] and hinder a community's lifeline to emergency services and evacuation routes.[91]

Tropical storms and hurricanes have been responsible for some of the Southeast's biggest and most damaging flooding events since 2018 (Figure 22.3). The likelihood of hurricanes slowing down or stalling near the coast has increased, exacerbating the rainfall-related flooding threat from these systems.[92] However, the impact of climate change on slowing down or stalling tropical storms remains uncertain,[92] although some simulations indicate a potential slowdown of Atlantic storms due to climate change,[93,94] including near the Southeast US coast.[95,96] In addition, rapidly intensifying hurricanes have presented challenges for implementing evacuations,[97] and the frequency with which Atlantic hurricanes rapidly intensify may be increasing in response to long-term human-caused climate change.[98] Also, there is evidence of increased intensification rates near the US Atlantic coast, which may continue into the future.[99] There have been significant improvements in understanding how nontropical systems,[100] atmospheric rivers,[101,102,103,104,105] past and future El Niño–Southern Oscillation patterns,[106,107] flash flooding,[73,108] and urban environments[109,110,111,112,113] add to the Southeast's risk of extreme precipitation and flooding.

With additional global warming, more North Atlantic hurricanes are expected to strengthen to at least Category 4 intensity and to undergo rapid intensification, sea level rise is expected to worsen storm surge inundation, and tropical cyclone–related rainfall is expected to increase.[93,114,115,116,117] The likelihood of storms making landfall could increase, which may offset the potential decrease in the total number of storms and overall exacerbate impacts.[118] However, some uncertainty remains regarding the expected degree of change in hurricane activity impacting the Southeast. Additionally, estimates suggest that some seasonal, annual average, and extreme precipitation amounts across the Southeast will increase, driven mainly by more extreme events (e.g., precipitation of 3 inches or more in 24 hours) at higher levels of warming.[20,67,119]

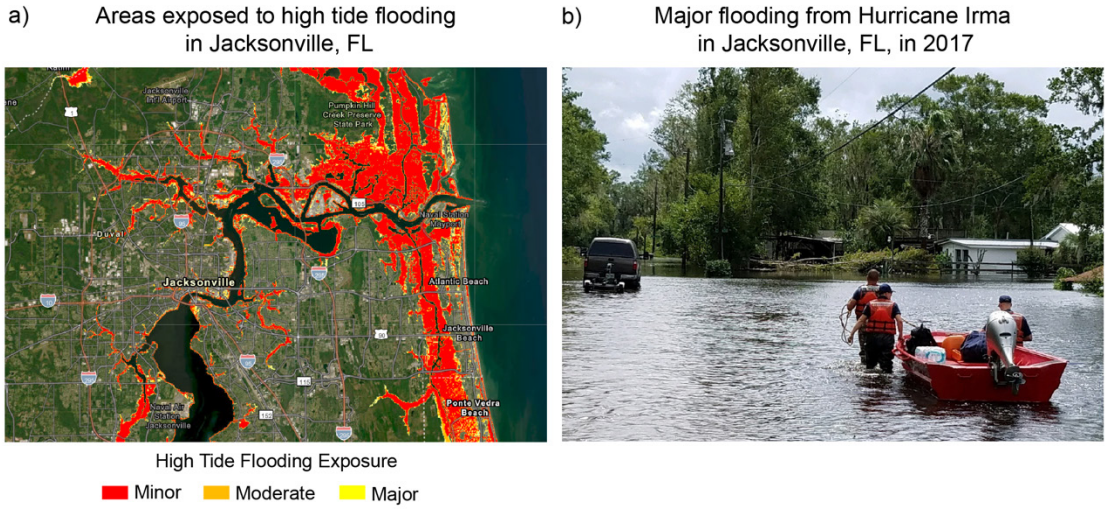
Some Southeast communities plan for these extreme events with an outdated understanding of climate-related risks.[68,120,121] Sewer infrastructure is built to accommodate a particular amount of rainfall over a specified time, and current estimates of precipitation intensity, frequency, and duration generally do not consider future projections of these metrics, posing a significant challenge to civil engineers.[122,123] Estimating future precipitation characteristics and their impact on sewer infrastructure in the Southeast is primarily conducted on a state-by-state basis and relies on different scientific approaches,[121,124] further complicating the development of design standards for climate-ready infrastructure (Figure 22.5; KM 12.2).[120]

Extreme rainfall that occurs at the same time that ocean water inundates populated areas (e.g., because of high tides or storm surges) creates compound flooding events, which can result in decreased property values[125] and roadway obstructions that can hinder first responders (KM 9.2).[66,126] Compound flooding events already affect low-lying areas in the coastal plain,[93,127] and the Intermediate-Low and Intermediate sea level rise scenarios for the Southeast project a higher frequency of compound flooding by midcentury in regions along the Atlantic coast.[128]

Tide gauges throughout the Southeast indicate that relative sea level rose by 6 inches during the 1970–2020 time period, with some variation across the region.[51] The average range of sea level rise by 2050 relative to 2000 in the Southeast (Low to High scenarios)[51] is 16–23 inches (0.40–0.58 m). This increases to a range of 2.2–7.3 feet in 2100 relative to 2000 under the same scenarios.[51] These regional estimates are higher than the projected global average rise due to regional variations in land motion, excessive groundwater pumping,[129] and the effects of sea level changes caused by changes in ocean currents.[51] For example, overall

sea level rise projections by 2050 are 22–32 inches for Grand Isle, Louisiana, 10–19 inches for Jacksonville, Florida, and 15–22 inches for Outer Banks, North Carolina. High tide flooding events in the Southeast may increase by a factor of 5–10 by 2050 due to sea level rise (Figure 22.5).[51] However, many communities will experience comparable increases in these events before 2050 due to changes in tides that exacerbate sea level rise.[52] Saltwater intrusion from rising sea levels has already degraded the health of coastal forests and estuaries while reducing their ability to store carbon,[130,131] and increased soil salinity has reduced yields in the remaining range and farmland.[132] While there is uncertainty in how global ice sheets will respond to additional global warming and thus ultimately determine longer-term sea level rise, the Southeast could experience 3.1–13.2 feet of sea level rise by 2150.[51]

### Sea Level Rise and Flooding in the Southeast




**Major flood events in Jacksonville, Florida, could become about 5 times more likely by 2050 under an Intermediate-High sea level rise scenario.**

**Figure 22.5.** Sea level rise under an Intermediate-High scenario[51] would drastically increase the likelihood of flood conditions by 2050. For Jacksonville, Florida (**a**), this would mean that "minor" flood conditions (red colors) will be about 30 times more likely, "moderate" (orange colors) will be about 20 times more likely, and "major" (yellow colors) will be about 5 times more likely. This would translate to more than 250 minor floods, 10–50 moderate floods, and about 1 major flood per decade in 2050. (**b**) Major flooding impacts would resemble those experienced during Hurricane Irma in 2017, when Jacksonville experienced record-high flooding conditions. (a) Adapted from NOAA/NOS/CO-OPS 2023.[133] Data layers provided by © Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community. (b) Photo credit: Department of Homeland Security.

## *Indigenous Communities: Loss and Leadership in a Rapidly Changing Region*

Indigenous communities have long faced displacement from and loss of cultural and desirable lands from settlers and government (Figure 16.1). Settler colonialism and climate change are forcing the displacement of Indigenous communities once again, causing stress and grief (KM 16.1). Indigenous communities experience substandard housing and infrastructure, as well as limited insurance coverage, which increases their vulnerability to climate stressors (KM 16.2).[134] In addition, land dispossession in the Southeast has impeded Indigenous Peoples from enduring climate hazards and deprived them of the benefits of the natural environments they once stewarded.[135,136,137,138]

Climate change and a shift from Indigenous-managed cultural landscapes to settler-managed landscapes threaten cultural knowledge and practices.[136] This shift can be seen in the loss of plants and animals of cultural significance to Southeast Indigenous communities (Figure 22.2; Box 22.3). This loss has contributed

to decreased physical and mental well-being as Tribal citizens have had to shift away from subsistence lifestyles that connect them to their cultural landscapes and contribute to cultural continuance.[22,139] Climate change also alters the ranges of native plants while enhancing the growth of invasive species that may out-compete them.[140] The loss of native species adversely affects Indigenous populations who rely on these resources for subsistence or cultural value,[141] such as coastal communities with economies driven by forests or fisheries.[142] However, Tribal Nations are finding ways to lead in responding to climate change (KM 16.3) while exercising their rights to cultural continuance and sovereignty through numerous actions and projects, including revitalizing rivercane ecosystems (Box 22.3).

Southeastern archaeological sites reveal a rich history of how Tribal Nations have met challenges similar to those they are experiencing now by using their Indigenous Knowledges.[143] However, many of these sites are exposed to the threat of rising sea level because they are located in coastal lowlands.[144] A sea level rise of approximately 3 feet (about 1 m) could result in the loss of more than 13,000 historic and prehistoric archaeological sites (with significantly more lost under more severe scenarios) while directly harming contemporary Indigenous communities across the Southeast.[144] Sea level rise also threatens coastal marshes in the Southeast more than anywhere else in the US.[145] The potential loss of these marshes, teeming with biodiversity and critical ecosystem services, could adversely affect the communities that depend on them. The ability of marshes to move (or "migrate") landward in response to sea level rise will depend on the availability of onshore land that in many cases is already developed. Planning for the migration of marshes will require a further understanding of their dynamics, as well as social trade-offs to accommodate their migration into new areas.[145]

## *Moving Out of Harm's Way, Protecting Existing Communities, and Planning Ahead for Growth and Potential Resettlement*

The Southeast is responding to climate threats; however, these actions are spread unevenly across the region (Figure 31.1). Many communities are adopting adaptation plans, including anticipating population growth due to climate-driven relocation.[146,147,148] Tribal governments achieve greater success in developing comprehensive climate adaptation plans when joining strong cross-Tribal networks that share knowledge of effective strategies.[149] However, Southeastern adaptation plans (especially for drought and heat) are less comprehensive than those in other regions.[150,151,152,153]

Adaptation actions include avoidance, planned relocation, protection, accommodation, or some combination of these. Avoidance involves limiting development in hazardous areas. Retreat from the coast or riverine floodplains involves removing infrastructure, housing, and public facilities from hazardous areas over time while limiting future development. Protection strategies use physical infrastructure like seawalls, levees, and beach nourishment, although these may not provide long-term protection if designed for past climate conditions.[154] Accommodation involves elevating structures or using building materials that can withstand being submerged by floodwaters or are less prone to damage when exposed to fire (Figures 22.6, 22.7).

Funding needed to implement adaptation projects remains elusive for many communities, especially those with limited resources and high levels of preexisting social vulnerability.[80,155] One strategy for advancing climate adaptation is applying for FEMA Hazard Mitigation Assistance (HMA) grants.[156,157,158] However, state hazard mitigation officers who manage these grant programs have described differing levels of capacity to help local governments develop and implement HMA grants.[16] While FEMA updated its hazard mitigation planning guidance in 2022 to require that local governments and states address equity and future conditions as part of their new strategic plans,[156] the impacts of these changes have yet to be effectively assessed relative to the quality of the plans. Despite these challenges, a growing number of localities are factoring intensifying climate-related stressors into adaptation plans[35,159,160,161] and helping guide new policy (Box 22.2).

## *Current Tools Could Ensure Equitable Adaptation*

There are several types of climate adaptation tools available to communities in the Southeast, including buyouts, information clearinghouses, land use policies, and city design and planning (Figures 22.6, 22.7).

Buyouts—acquiring hazard-prone housing that is demolished and converted to open space—are widely recognized as one of the most cost-effective strategies for reducing future losses,[162,163] including those associated with adapting to a changing climate.[164] However, while buyouts do require that the land be converted to open space after purchase, applying other proactive land-use planning techniques that guide development to safer locations or limit future growth in hazard-prone areas remains an uncommon practice.[165,166] As a result, there remains considerable uncertainty around whether communities are actually reducing risk when accounting for the losses avoided with buyouts relative to increased hazard exposure associated with new development in hazard-prone areas.[167,168,169] For example, some buyouts resulted in people relocating to an area of similar risk as their original dwelling,[170,171] and relocation in a broader context has meant moving from one risk zone to another.[172] Buyouts can also reduce a community's tax base, which can be particularly devastating in smaller jurisdictions with limited revenue to support governmental services.[173] Questions of equity in buyouts include whether buyouts are preferred by residents, whether choosing to participate in buyouts is in their best interest, and whether frontline communities are involved in deciding how and where buyouts occur (KM 20.5; Figure 20.3).[174,175,176,177,178,179] Additional buyout challenges include the long-term management of resulting open spaces, tracking buyout land in a given area, and strategies to achieve co-benefits such as creating climate-resilient recreation amenities like parks, greenways, water retention areas, and ballfields.[180,181,182] Buyout migration and relocation from one place may also exacerbate local housing pressure in another. For example, in Miami, wealthier individuals are moving from higher-flood-risk coastal areas to safer higher-elevation areas, increasing inland property values and displacing residents,[183,184,185] although the exact pressures driving gentrification and displacement within any community are complex.[186,187] There is evidence that points to the migration of some Black residents out of floodplains in the Southeast, including the case of Edgecombe County, North Carolina, where the Town of Princeville, discussed in Box 22.1, is located.[53]

A growing number of climate adaptation resource clearinghouses are available (KM 31.4), and they include Southeast case studies.[188,189] In addition, Southeast-focused organizations like the Southeast Climate Adaptation Science Center, USDA Southeast Climate Hub, and the Southeast and Caribbean Disaster Resilience Partnership provide resources needed to advance adaptation strategies, including resources for rural and/or under-resourced communities.[18,64] Some climate change planning documents even now center on additional considerations such as equity in their frameworks.[190] However, inequitable access to resources and constraints on workforce capacity to effectively use these tools can also lead to unequal progress toward implementing strategies across communities.

Climate-resilient community design principles are being employed by urban planners, landscape architects, and architects, as well as by an increasing number of municipalities (Figures 22.6, 22.7, 12.8).

## Climate-Resilient Neighborhood Design

**Climate-resilient community design can ensure the long-term vitality of cities.**

**Figure 22.6.** Climate-resilient urban design may incorporate nature-based, infrastructural, and community-based solutions to alleviate the harm from climate stressors such as extreme heat and flooding. Participatory processes can foster shared ownership of climate resilience strategies and promote the distribution of resources to where they're needed most. Equitable reduction of climate risks and ensuring the reliability of critical services can create social benefits. Figure credit: Groundwork USA and North Carolina State University.

## Box 22.1. Reducing Flood Risk in Princeville, North Carolina

Land-use decisions dating back to the post–Civil War Reconstruction era placed Black communities in lower-lying, historically flood-prone areas across the Southeast. One example is the community of Princeville, North Carolina, located along the Tar River.[191] Princeville is the oldest incorporated independent Black community in the United States, originally settled by formerly enslaved people.[192] The town, located entirely in a floodplain, has flooded numerous times. In 1967 the US Army Corps of Engineers constructed a levee that protected Princeville until Hurricane Floyd struck in 1999 and caused widespread flood damage to the town.[192] Research suggests that repeated exposure to varied water levels over time has reduced the levee's protective capacity.[193] Although state officials offered to use buyouts to move the town to higher ground following Hurricane Floyd, residents refused due to their deep attachment to the place.[194] In 2016, Hurricane Matthew flooded Princeville again. Residents then accepted the state's offer to fund several risk-reduction measures, including buyouts, converting acquired land to open space, elevating homes, and building replacement housing in compliance with local flood standards. The state also purchased a 52-acre parcel of land adjacent to the town's borders but located outside of the 100-year floodplain where critical facilities, businesses, and new housing are to be built.[173] Princeville provides a powerful example of how existing post-disaster funding programs and policies can guide risk reduction and adaptation in the face of a changing climate. The long-term impact of these programs on the community's overall social and physical cohesion, as well as their resilience to future storms, remains an open question.

## Box 22.2. Reshaping FEMA Policy to Aid Disaster Recovery in the Gullah Geechee Cultural Heritage Corridor

The Gullah Geechee Cultural Heritage Corridor is a National Heritage Area established by Congress to recognize the unique culture of the Gullah Geechee people who have traditionally resided in the coastal areas and the sea islands of North Carolina, South Carolina, Georgia, and Florida —from Pender County, North Carolina, to St. Johns County, Florida.

Communities often consist of coastal families who represent five or more generations of Gullah Geechee heritage and whose quality of life is inextricably connected to the environment and the ecosystem services it provides. Gullah Geechee residents and other coastal citizens who reside on heirs' property, or property passed down through family members by inheritance, are highly vulnerable to negative impacts associated with extreme weather events and changing climate and ocean conditions. One such impact was former federal disaster aid policies that did not recognize the uniqueness of heirs' property, where possession is authentic but documentation can be complicated. The Gullah Geechee Cultural Heritage Corridor worked with FEMA to identify policy barriers and revisions for Gullah Geechee citizens seeking disaster and recovery aid. The Corridor used its communication network to educate communities about the newly created disaster aid revisions made to support owners of heirs' property before the 2022 hurricane season. When powerful storms struck communities in South Carolina, the Corridor team reached out to families and directed FEMA representatives to areas that were hardest hit. Through its community-driven ad hoc subcommittee on natural resources and climate change, the Corridor has also used a similar grass-roots approach to understand how climate change may be experienced differently in the coastal communities of the Corridor and has worked to identify nature-based solutions that may benefit some communities.

### Climate Resilience in the Southeast

**Southeast communities are adapting to climate threats in a number of ways.**

**Figure 22.7.** (**top left**) A 60,000-acre-foot stormwater reservoir in Palm Beach County, Florida, temporarily stores peak stormwater flows. (**top right**) Transit advocates in Richmond, Virginia, document the cooling efficiency of shade structures at public bus stops. (**bottom right**) Construction workers prepare to raise a home's foundation along Virginia's Eastern Shore. (**bottom left**) Rain gardens like this one can be highly place- and community-driven projects to absorb excess stormwater and improve green space, while nonprofits like Groundwork RVA build skills for a green economy. Photo credits: (top left) South Florida Water Management District [CC BY-ND 2.0]; (top right) © Jeremy Hoffman, Science Museum of Virginia; (bottom left) © Robert Jones; (bottom right) Aileen Devlin, Virginia Sea Grant [CC BY-ND 2.0].

## Key Message 22.2

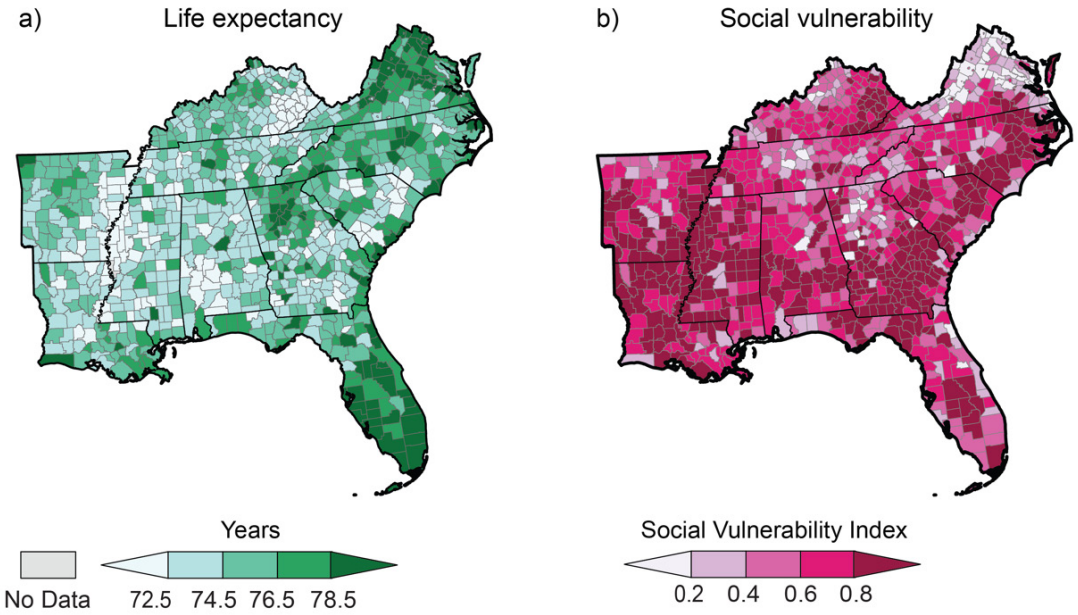
## Climate Change Worsens Human Health and Widens Health Inequities

Human health and climate stressors are intimately linked in the Southeast (*very high confidence*). Community characteristics such as racial and ethnic population, chronic disease prevalence, age, and socioeconomic status can influence how climate change exacerbates, ameliorates, or introduces new health issues (*very high confidence*). Climate change is already impacting health in the region (*very likely*, *very high confidence*). There are effective strategies to address the health impacts of climate change in the Southeast that have multiple benefits across social and environmental contexts (*high confidence*).

### *Underlying Health Issues and History in the Southeast*

Public health status is an important indicator of vulnerability to climate stressors,[190,195] and Southeasterners are consistently ranked among the unhealthiest in the Nation, with shorter life expectancies than the US average (Figure 22.8).[196] Health disparities in the Southeast are related to various social determinants of health, such as lack of access to healthcare, low socioeconomic status, and poor health behaviors (e.g., smoking and drug and alcohol abuse).[197] Sedentary lifestyles are reinforced by the quality of the surrounding built environment: the Southeast is home to 8 of the 10 least-walkable cities,[198] 15 of the 20 most dangerous cities for pedestrians,[199] and 4 of the top 10 deadliest states for cyclists in the United States.[200]

### Present-Day Health Inequities




**Present-day health inequities in the Southeast exacerbate climate-related risks.**

**Figure 22.8.** (**left**) Southeastern states rank among the lowest in the Nation for life expectancy, although there is considerable variation within the region and within individual states. These patterns in life expectancy are reflected in estimates of social vulnerability (**right**)—a measure of how societal stressors like poverty, crowded housing, older populations, and lack of access to transportation may diminish a community's ability to avoid human distress and financial damages in a disaster like those made worse by climate change. Figure credits: (left) Groundwork USA, NOAA NCEI, and CISESS NC; life expectancy data from University of Wisconsin Population Health Institute, County Health Rankings & Roadmaps 2022, www.countyhealthrankings.org; (right) Science Museum of Virginia, NOAA NCEI, and CISESS NC.

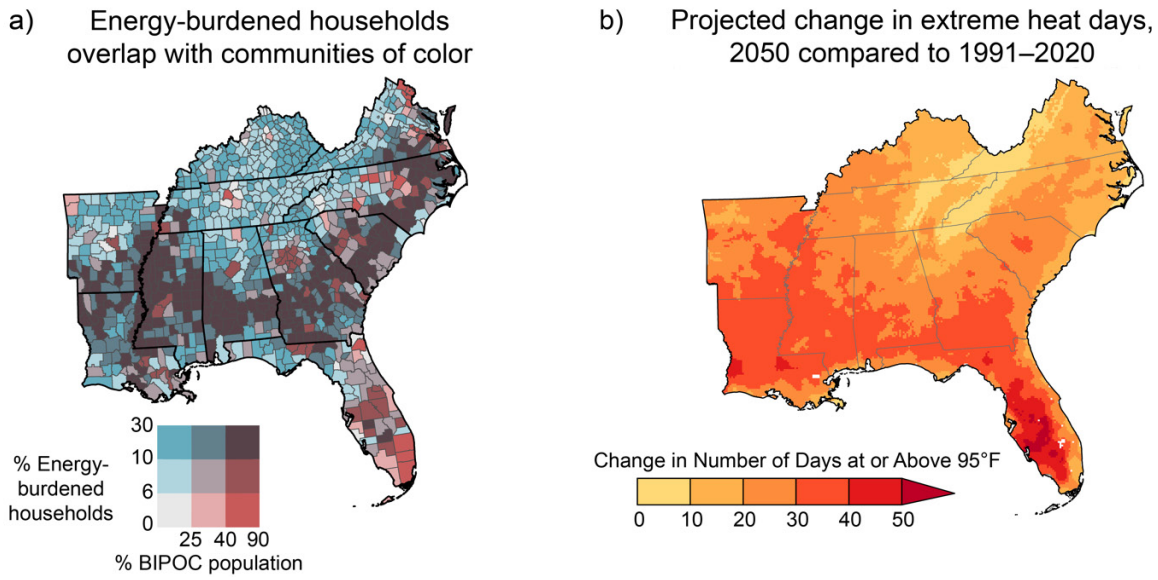
The Southeast has more Black residents than any other NCA region,[40] and health-related challenges faced by communities with majority Black populations differ from those with majority White, Hispanic, or Asian populations.[201] Communities with majority Black populations tend to have even lower life expectancies and less access to resources that promote health, such as grocery stores, safe places to exercise, and quality healthcare than whiter and wealthier populations.[202] These communities also have fewer opportunities for economic prosperity (Figure 22.12), fewer employment opportunities, limited access to quality education, and higher unemployment rates, all of which shape health outcomes.[11] Black communities in the Southeast, therefore, shoulder a disproportionate level of health risk associated with climate change.[3,12]

## *Keeping Cool as Temperatures Rise*

Extreme heat affects everyone, but particularly at risk are pregnant people;[203,204,205] people with heart and lung conditions;[206,207] older adults and young children;[208,209] people with mental health conditions;[210,211] outdoor workers in construction, agriculture, and the service industry;[212,213] athletes;[214,215,216] and populations who lack adequate shelter or are incarcerated.[217,218]

Southeasterners rely on air-conditioning to cool living spaces, and air-conditioning demand is expected to grow across the Southeast as the climate warms.[219] However, air-conditioning prevalence varies along racial and economic lines.[220] Furthermore, the Southeast has high rates of households that experience energy insecurity.[221] While the Southeast has the lowest energy rates in the US, households there pay the country's highest energy bills.[222] High energy bills disproportionately impact rural and under-resourced residents, elderly residents on fixed incomes, and communities of color (Figure 22.9).[222] Historical *de facto* as well as *de jure* segregation policies such as redlining—the New Deal–era practice of classifying communities with significant Black, Asian, and immigrant populations as hazardous for financial investment—neighborhood housing covenants, and urban renewal have had lingering effects on frontline communities in the Southeast, resulting in their low proportion of homes that are energy efficient and affordable.[222] There is evidence that the number of blackout events (power outages) affecting more than 1,000 residents for more than one hour due to increasing energy demands and extreme weather events is increasing.[223,224,225] The Southeast has experienced many such blackout events annually and during the warm season (May–September) since 2011 (Figure 22.10).[226]

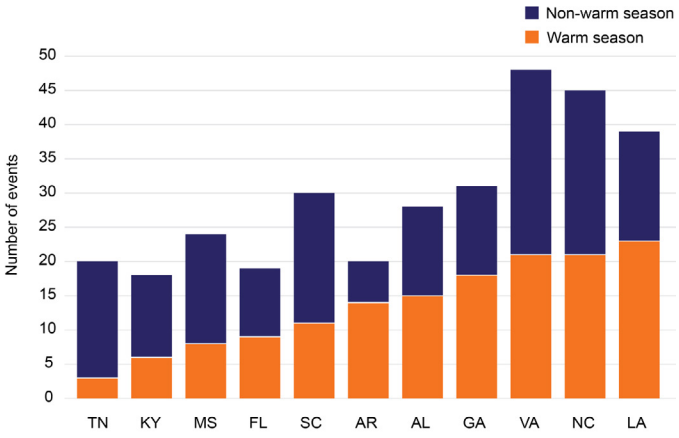
## Inequitable Heat Burden and Future Heat Exposure




**Projected increases in heat extremes disproportionately affect communities of color and other energy-burdened groups.**

**Figure 22.9.** Present-day inequities will be amplified by the increased threat of extreme heat in the future. Panel (**a**) shows overlap between the percentage of the population that is BIPOC (Black, Indigenous, and People of Color) and the percentage of low- and moderate-income households with a high energy burden, or households that spend a disproportionately high amount of money on energy costs relative to their income. The dark purple areas show high overlaps between BIPOC households and high energy burden. Panel (**b**) shows the projected increase in the number of extreme heat days (maximum temperature at or above 95°F) in 2050 relative to 1991–2020 under a high scenario (SSP3-7.0). Figure credits: (a) adapted from Bryan 2020;[227] (b) NOAA NCEI and CISESS NC.

## Blackouts Affecting More than 1,000 Residents for More Than 1 Hour (2011–2021)




**Warm-season blackouts add to heat-related risks for residents in Southeast.**

**Figure 22.10.** For several Southeast states, major blackout events occur most often during the warm season (May–September). Major blackouts during the warm season generally occur during heatwaves, placing people at higher risk of heat exposure and heat-related illness because they do not have access to air-conditioning. The figure shows reported major blackout events—defined as electrical grid failures affecting more than 1,000 residents for more than 1 hour—in Southeast states during 2011–2021. Data are presented as warm season (orange, May through September) and non-warm season (blue, October through April). Figure credit: Georgia Institute of Technology, Groundwork USA, CDC, NOAA NCEI, and CISESS NC.

Public cooling centers are temporary health interventions for those without adequate air-conditioned shelter on exceptionally hot days (KM 15.3). However, in some areas of the Southeast, these centers are not located within walking distance of the populations most in need.[228] Furthermore, the Southeast has the lowest public transportation access for households without a private vehicle.[229]

Heatwaves in the Southeast are happening more frequently and are occurring during a longer heat season, with some cities also showing increasing trends in their duration and intensity (Ch. 2).[3,230,231] The number of extreme warm days (above 95°F) is expected to continue increasing with every increment of global warming (Figure 22.9b; Ch. 2). Wet-bulb globe temperature (WBGT)—which measures the combined effects of temperature, humidity, wind, and sunlight on thermal comfort and which may be a better metric for the Southeast than more traditional measures of extreme heat[232,233]—has already increased due to anthropogenic climate change in parts of the region[234,235] and is expected to increase across the region throughout this century.[230,235] Additional heat stress within cities can be attributed to the urban heat island effect (Figure A4.4), whereby cities experience warmer temperatures than outlying rural areas and some neighborhoods within a city are hotter than others.[236,237] Heat island intensities across the Southeast are systematically higher in formerly redlined communities[5] and in counties with higher proportions of Black, Hispanic, and Asian residents, people with education no higher than a high school diploma, people with lower median incomes, and single-parent households.[238] However, there is a lack of consistent and appropriate thresholds used to evaluate heat risk. For example, most work-related heat illnesses across five Southeast states occurred below the heat index range designated as dangerous by the National Weather Service.[239]

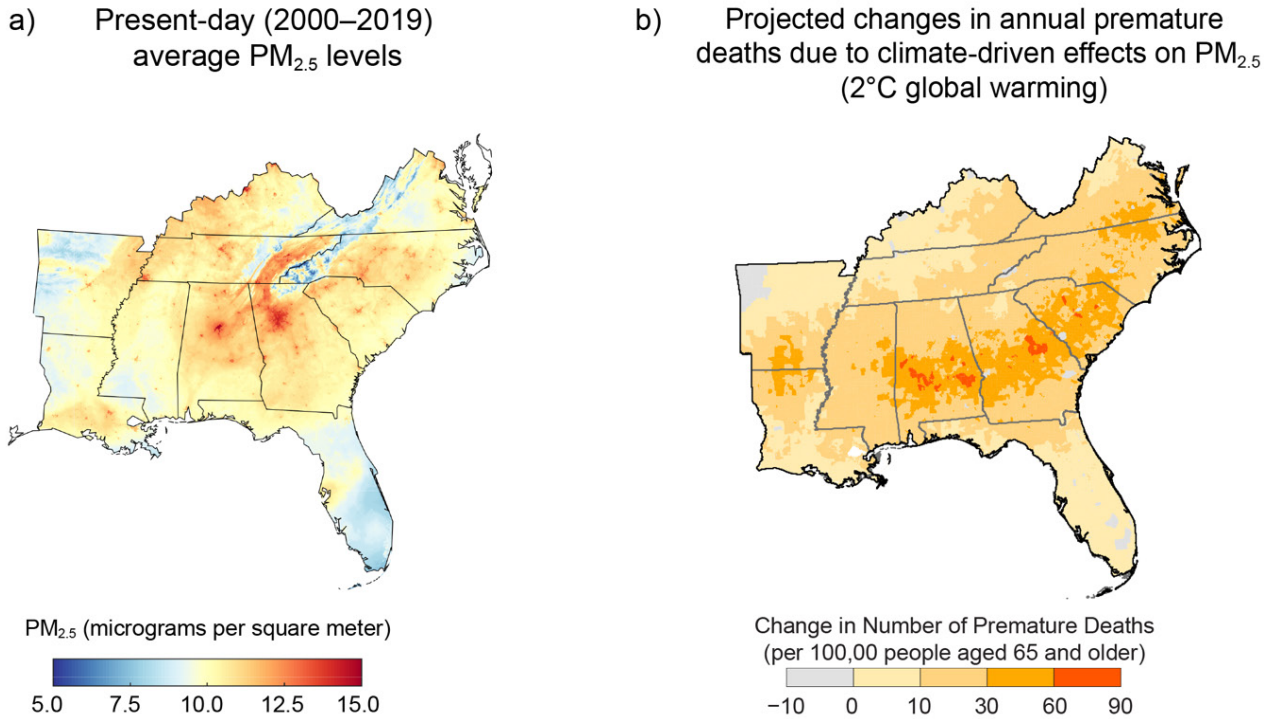
Climate change is increasing the risk of multiple dangerous weather events occurring simultaneously or in close proximity, resulting in worsened health effects (Ch. 15). An example of this is when a heatwave occurred after Hurricane Laura devastated the coast of Louisiana in 2020, resulting in at least eight deaths due to heat and an increased risk of heat-related illness, particularly for those who lost electricity and outdoor workers assisting with the recovery.[240]

In response to heat threats, Miami has institutionalized the first city heat officer to coordinate heat preparedness and response efforts to reduce impacts to the most vulnerable.

## *Blowing in the Wind*

In the Southeast, climate change threatens Clean Air Act improvements by creating favorable conditions for increases in smog[241,242,243] and wildland fire emissions.[244,245,246] The Southeast already has significant amounts of particulate matter ($PM_{2.5}$; Figure 22.11a) as a result of anthropogenic pollutants[247] and extensive vegetation,[248] and the associated health effects are experienced disproportionately by communities of color and populations with lower socioeconomic status (Ch. 14).[249,250] Future premature deaths due to $PM_{2.5}$ in the region could be avoided through significant emissions reductions, even when considering future warming (Figure 22.11b; KM 14.3).[3,251,252] This is particularly relevant to the Southeast, which is projected to have the highest number of premature deaths due to climate-induced increases in $PM_{2.5}$ and ozone exposure.[3,251,252]

### Current $PM_{2.5}$ Levels and Projected Change in Deaths Due to $PM_{2.5}$ at 2°C of Global Warming




**Rising levels of air pollution from a warming climate pose profound threats to human health.**

**Figure 22.11.** (**a**) Present-day (2000–2019) patterns of particulate matter ($PM_{2.5}$) pollution in the air are associated with excess mortality. (**b**) Potential future patterns (projected changes at 2°C of global warming relative to the 1986–2005 average) of premature deaths in people aged 65 and older due to $PM_{2.5}$ show that even when accounting for reduced particulate emissions in the future due to developments such as vehicle electrification, the Southeast is particularly sensitive to increases in $PM_{2.5}$ from increased temperature alone. (a) Adapted from van Donkelaar et al. 2019.[247] (This is an unofficial adaptation of an article that appeared in an ACS publication. ACS has not endorsed the content of this adaptation or the context of its use.) (b) Adapted from EPA 2021.[3]

In addition, airborne pollen can pose significant health risks to populations living in the southeastern United States.[253] Since 1992 in Atlanta, tree pollen concentrations have increased by approximately 4% in the spring and 10% in the fall, and weed pollen has increased by approximately 5% in the spring.[254] Some species of trees and weeds are exhibiting an earlier and longer pollen season, correlating with warmer spring temperatures.[254] Pollen increases pose significant health risks, including aggravating respiratory conditions such as asthma, which has been linked to a loss of school and work days (KM 14.4). These health risks are expected to worsen as pollen seasons shift earlier and lengthen due to climate change (KM 14.4; Figure 8.2).

## Fire Danger

Wildfire risk disproportionately disrupts the lives of socioeconomically disadvantaged communities in the Southeast.[2] As more people inhabit forested areas, there is an attendant increase in wildfire risks to human health and property.[255] More hot days may also exacerbate soil moisture deficits, leading to heightened wildfire risk in the region.[244,256] Rural, mountainous portions of the Southeast are more exposed to and less equipped for mitigating wildfire.[257]

Forest managers conduct controlled, low-intensity fires, known as prescribed burns, to reduce the amount of deadwood and vegetation, thereby managing wildfire risk.[258] While the impacts of wildfires on air quality are widely recognized (KM 14.2), less is known about the impacts of prescribed burns versus wildfires on air quality.[246,259] Prescribed burns reduce the risk of wildfire damage to the environment, homes, and infrastructure, although areas with intensive prescribed burning tend to be near communities with higher social vulnerability scores, which subsequently experience more negative health outcomes from the smoke.[260,261] As conditions favorable for wildfire and unfavorable for prevention become a greater risk for southeastern communities due to a warming and drying climate,[256,262] communities may need to invest in more robust equipment and infrastructure. In 2016, wildfires in western North Carolina and eastern Tennessee highlighted the connection between exceptional drought and fire in the Appalachians.[263] Power outages and damage to PVC pipelines that supplied water to sprinkler systems led to a lack of water to combat fires, resulting in more significant damages.[264,265] That year, nearly 50% of US wildfires occurred in the Southeast, yet these fires contributed to only 29% of the total area burned that year, indicating that southeastern wildfires are smaller.[244,246,258]

## Rolling Red Tides

Harmful algal blooms (HABs), also known as red tides or brown tides, occur in fresh, brackish, and salt water.[266] HABs result from the overgrowth of algae due to runoff water containing excess nutrients from agriculture and lawn maintenance, rising water temperatures, and other land-use development.[267] Since 2011, large masses of sargassum, which can fall under a HAB classification, have been increasing from Florida across the Caribbean, causing harm to coastal social–ecological systems. This problem could be intensified by rising temperatures from climate change.[268,269] HABs have significant negative impacts on human and animal health, as well as broad-reaching environmental and economic effects.[270,271,272,273]

Humans may experience various health issues from HAB exposure, such as diarrhea and headache.[273] HAB events also threaten national and local economies, as tourist areas become less desirable to visit.[271] Fisheries and aquaculture industries suffer from the loss of marine life and decreased species diversity as ecosystems are disrupted and hypoxic conditions occur,[274,275,276] and consumers are potentially exposed to seafood poisoning.[277,278] On Florida's Gulf Coast, prolonged algal events have caused a devaluation of coastal properties.[270,272]

## More Than Just a Bug Bite

Temperature and precipitation changes are anticipated to shift the geographic distribution and season of certain disease-carrying mosquitoes and ticks in the Southeast (KMs 15.1, 8.2). For ticks that carry diseases such as Lyme and Rocky Mountain spotted fever, models project varying shifts in ecosystem suitability in the Southeast depending on the species, land-use changes, and host abundance.[279,280,281,282,283] Of particular concern are mosquito-borne diseases such as chikungunya, dengue, malaria, West Nile virus, and Zika virus. All have been documented in the Southeast and pose potential risks to human health.[284] Black and under-resourced neighborhoods in Chatham County, Georgia, were identified as hotspots for West Nile virus, as well as being home to communities with limited understanding of personal risk and protective measures against mosquitoes.[285,286]

## *The Mind–Climate Connection*

The Southeast is home to 5 out of the 10 highest-ranked states for the prevalence of mental illness[287] and 8 out of the 10 lowest-ranked states for access to mental healthcare services.[288]

Climate change significantly affects mental health as a result of 1) acute disaster events such as hurricanes, floods, and wildfires (KM 15.1); 2) long-term changes such as drought[289] and heat stress;[210] and 3) existential threats of long-lasting climate change impacts that make people feel less secure in their physical environment.[290] Those who are either directly impacted by or concerned about the threat of climate change to themselves or others may experience "eco-anxiety" or "climate anxiety."[291,292]

While extreme weather events commonly occur in the Southeast, climate change has increased their frequency and magnitude (Ch. 2), causing residents to face repeated trauma and displacement at an unprecedented level, which can lead to stress and the onset of new psychiatric disorders or the worsening of preexisting mental health conditions,[293] especially among children and under-resourced and BIPOC residents.[290,294,295] The Florida Department of Health in Monroe County conducted an evaluation of its emergency shelter effectiveness in serving people with particular access and functional needs and found significant room for improvement, leading to updates to strategic planning processes and procedures related to the operation and communication of specialty emergency shelters to ensure more equitable access to shelter services.

### Key Message 22.3

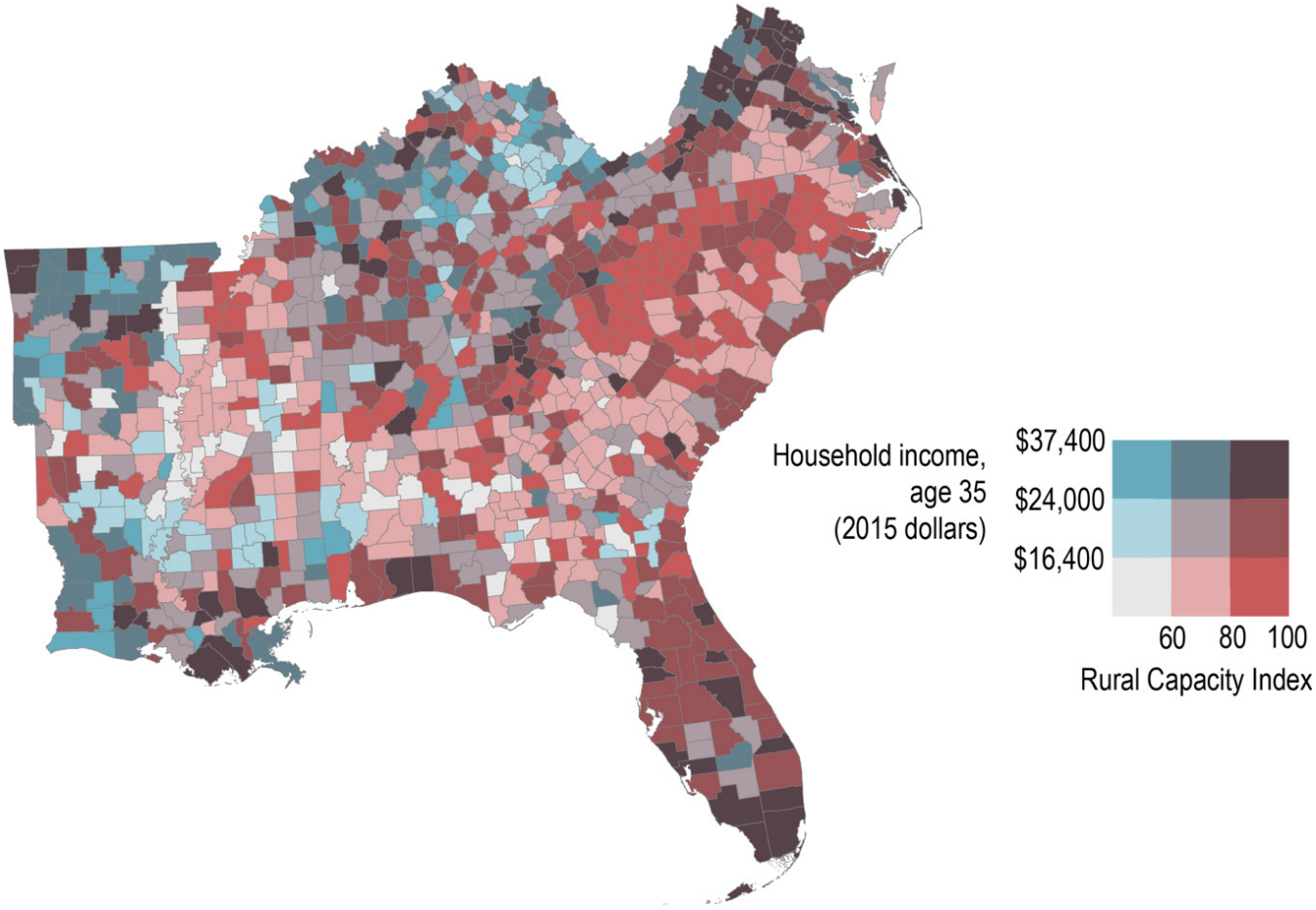
### Climate Change Disproportionately Damages Southeastern Jobs, Households, and Economic Security

Over the last few decades, economic growth in the Southeast has been concentrated in and around urban centers (*high confidence*) that depend on climate-sensitive infrastructure and regional connections to thrive (*medium confidence*). Simultaneously, rural and place-based economies that rely on the region's ecosystems are particularly at risk from current and future climate changes (*very likely*, *high confidence*). Global warming is expected to worsen climate-related impacts on economic systems, labor, and regional supply chains in the Southeast, with disproportionate effects on frontline communities (*very likely*, *high confidence*). A coordinated approach that recognizes present-day inequities and the interdependencies between rural and urban communities will be necessary to secure the region's economic vitality (*very likely*, *high confidence*).

## *Economic Risks in the Southeast: "Less Money, More Problems"*

Across the Southeast, disaster losses have increased over the last several decades, primarily due to rapid growth in hazardous areas that are driven, in part, by national, state, and local policies that incentivize development in such areas.[166,296,297] Rising disaster costs negatively impact local and regional economies, some of which are already affected by limited upward economic mobility for their population, as well as by limited administrative, institutional, and social capacity (Figure 22.12). Moreover, these multisectoral impacts are expected to worsen substantially due to climate change,[298] especially in the Southeast region (Figures 22.13, 22.14, 19.1; KM 19.1).

## Household Income and Rural Capacity for Action

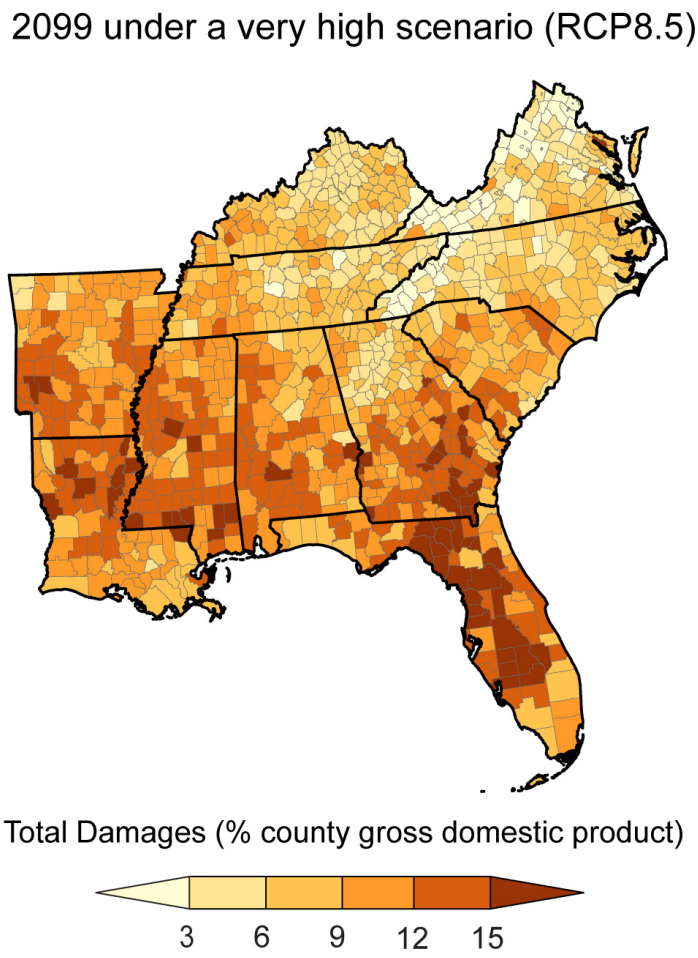



**Counties where low-income households overlap with limited community capacity (shown in light gray) highlight rural climate risk challenges.**

**Figure 22.12.** In the Southeast, children born to parents who make the lowest incomes also tend to earn low incomes as adults (blue hues), especially within frontline communities. These pockets of limited generational upward mobility may also overlap with lower scores on the Rural Capacity Index (red hues), as measured by under-resourced governance structures and limited public participation in civic processes like voting.[64] This lack of resources may leave these communities more at risk from damage due to climate change. Figure credit: EPA, Groundwork USA, NOAA NCEI, and CISESS NC.

Losses attributed to climate change are expected to increase as rapid development continues to occur in hazardous areas, particularly along coasts (Figure 22.4b),[299] while rural residents face increasing levels of isolation and economic decline (Figure 22.12).[62]

## Projected Annual Economic Damages from Unmitigated Climate Change




**The Southeast region faces substantial economic risks from climate change impacts.**

**Figure 22.13.** Direct annual climate damages, as measured by the percent of county GDP, are projected to be especially large in the Southeast. The map shows damages under a very high scenario (RCP8.5) at the end of the century. Adapted from Hsiang et al. 2017.[300]

## Regional Impacts of Extreme Weather Events

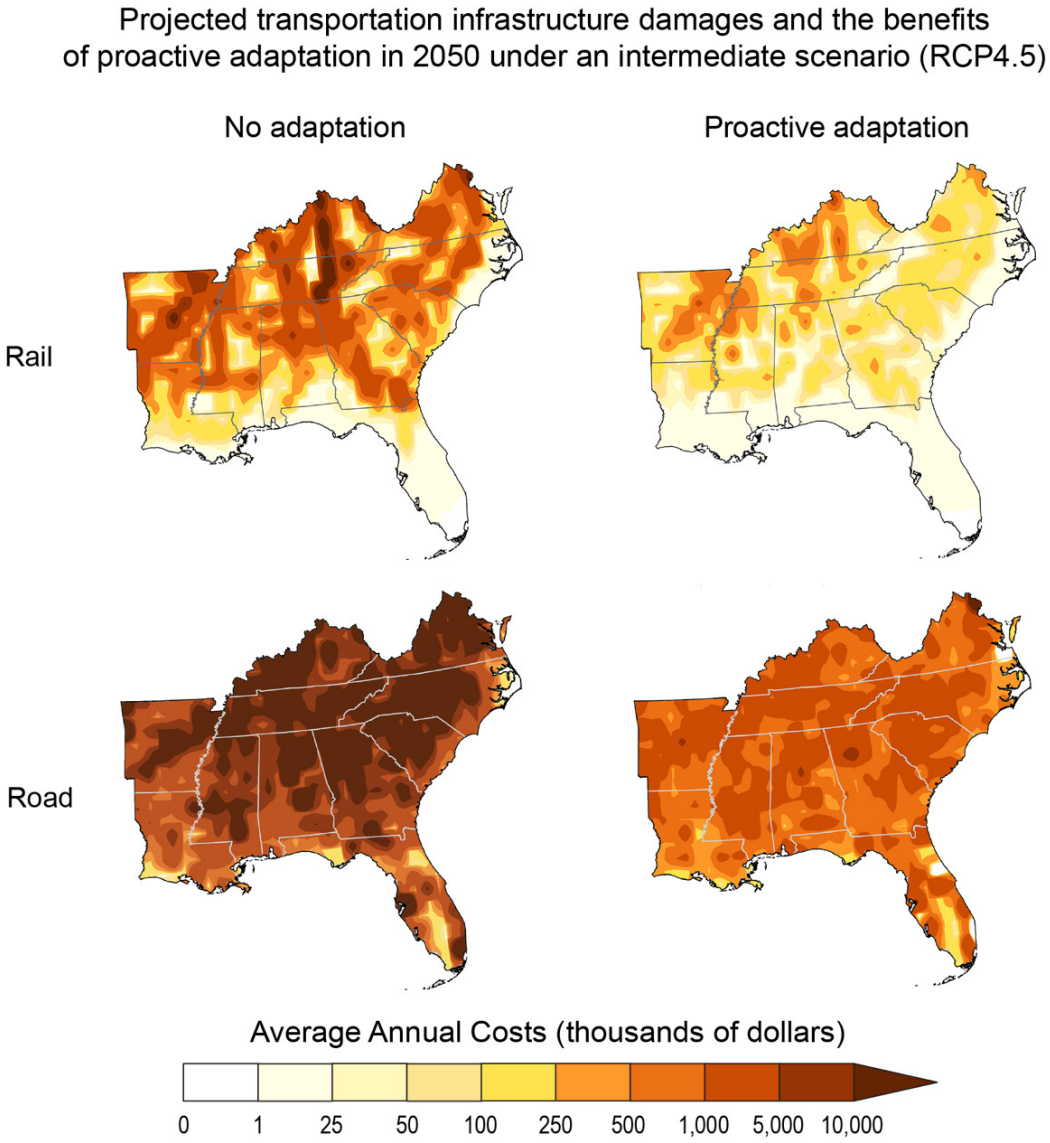
**The Southeast is impacted by a wide variety of extreme weather events.**

**Figure 22.14.** The impacts of weather and climate extremes can be seen in photos from the Southeast (**clockwise from top left**): A flooded neighborhood in Kissimmee, Florida, is shown after Hurricane Ian (2022), which heavily impacted local livelihoods. Drought conditions in Alabama (2016) directly impacted farmers' incomes and potentially increased prices for customers. Regional drought-induced low-flow conditions on the Mississippi River caused barges and towboats to become stranded for several days (2022). Flood damage in northeast Arkansas impacted transportation infrastructure and crops and may have impacted supply chains (2017). Image credits: (top left) Robert Kaufmann/FEMA, DHS; (top right) Bruce Dupree, Alabama Extension [CC0 1.0]; (bottom left) Sonny Perdue, USDA; (bottom right) adapted from NASA Earth Observatory.

Place-based economies that are located in hazardous areas and are reliant on unique ecological systems (e.g., aquaculture, farming, and recreation/tourism) face numerous challenges, including the uncertainties associated with the stability of freshwater and saltwater ecosystem services that support business and cultural attachment to place.[301] For example, some fishing communities are facing threats to fishing infrastructure due to sea level rise and more intense coastal storms, as well as threats to fisheries stock habitats that are vulnerable to the effects of a changing climate, such as increasing bottom-water temperatures.[142,302,303] Meanwhile, inland towns and cities with ecotourism attractions also face significant economic losses due to increased flash flooding,[73,108] including lower-income rural areas in Appalachia, as exemplified by the 2022 floods in eastern Kentucky. Rapidly growing urban centers in the Southeast are increasingly vulnerable to drought and the challenges tied to the provision of water for residents and businesses.[304,305,306,307] The Southeast is more drought-prone than other parts of the eastern US due to higher rates of evapotranspiration.[308,309] Evapotranspiration is expected to increase due to future climate warming (Ch. 2). Alabama cities' drought plans were evaluated as less comprehensive and lacking pre-drought preparation compared to those of California cities.[152] In rural, agriculturally dependent economies, increased heat, drought, and water-laden tropical storms currently threaten the productivity of crops and livestock (KM 22.4),[310,311] as well as the health and livelihoods of workers, who tend to be Latino migrants.[312] Future global warming will increase this threat, potentially further reducing labor productivity and costing billions

of dollars, particularly in the already hot and humid Southeast (KM 2.2).[212,313] The Southeast's economy relies on the region's ports, rivers, rail, air, and road networks, which are at risk from sea level rise, flooding, extreme heat, drought, and other climate-related hazards.[61,314] However, proactive adaptation can offset potential future climate-related damages substantially (Figures 22.13, 22.15, 22.17). Unplanned disruptions to these systems can potentially affect consumer pricing of goods, services, and livelihoods throughout the region and elsewhere (Figure 22.16).[315,316]

## Proactive Adaptation Offsets Future Transportation Infrastructure Costs




**Proactive adaptation to climate change could save millions of dollars in future transportation infrastructure costs.**

**Figure 22.15.** Future climate change impacts (under RCP4.5) may cost US transportation infrastructure billions in damages by 2050, with especially high costs in the Southeast. The **left panels** show the additional annual average system costs (as compared to 1986–2005 in 2018 dollars) to rail infrastructure (**top**) and road networks (**bottom**) in 2050, assuming no adaptation. Proactive adaptation—anticipating climate risks and investing up front in strengthening these systems before damage occurs—could reduce significantly, but not eliminate, these costs (**right panels**). Proactive adaptation strategies include temperature sensors for railroad tracks and working to reduce disruption times for roads undergoing repairs. Adapted from Neumann et al. 2021[317] [CC BY 4.0].

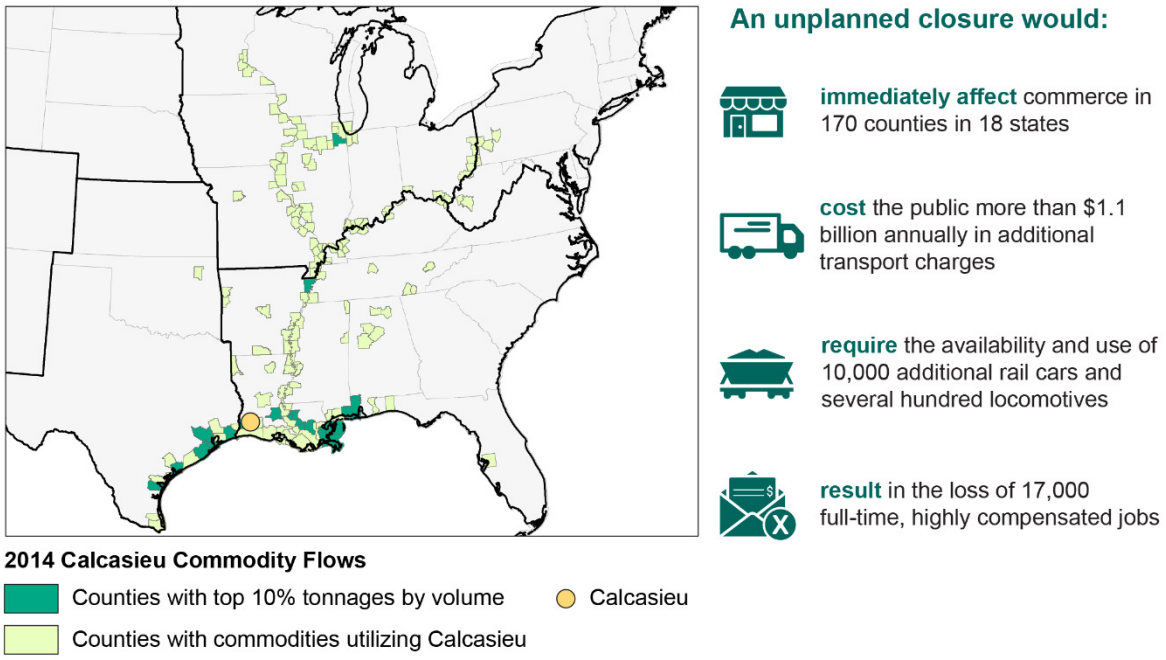
## *Supply Chain Impacts Affect Places Outside the Southeast*

There is an urgent need to address climate change risks to global supply chains (Focus on Risks to Supply Chains; KM 19.1).[318] In the Southeast, climate change–induced transportation infrastructure risks affect all modes (e.g., air, water, highway, rail, and even pipelines; Figures 22.15, 22.16; Ch. 13). Transportation agencies across the region appear to be planning for infrastructure improvements on different schedules and often lack the capacity to include climate data in the planning process (Ch. 13).[319] Coordinated and proactive adaptation strategies could offset significant future damage to these systems (Figures 22.15, 22.17).[317,320,321]

Many Southeast roadways and rail lines are located along waterways and frequently cross bodies of water, making them vulnerable to potential floods and heat-related impacts. High future costs are expected if no adaptive investments are made today (Figures 22.15, 22.17).[317] Inland navigation and the Mississippi River are critical to supply chains in the Southeast and much of the central portion of the United States, as evidenced by the 2021 closure of the Interstate 40 bridge over the Mississippi River at Memphis, Tennessee.[322] Unscheduled lock outages resulting from floods, droughts, earthquakes, or hurricanes can cause cascading impacts. For example, an unplanned outage of the Calcasieu Lock in southern Louisiana would affect economies in 170 counties and 18 states (Figure 22.16).[315,323] In the Southeast, manufacturing facilities for industries such as automotive (including electric vehicles and charging stations),[324] solar panels, agriculture,[325] and construction often rely on parts or materials originating from other locations, including some from international sources. The Mississippi River serves as a gateway to the Nation for imports of such materials and exports of goods such as agricultural products. In recent years, low-flow conditions due to regional droughts on Southeast waterways such as the Mississippi have halted or delayed the movement of barges carrying bulk goods, with regional and national implications (Figures 22.14, 22.16).[326,327]

Disruptions can impact not only the delivery of finished goods and products to customers but also production and the livelihoods of individuals working in jobs dependent on materials from other locations that may not arrive in time, leading to revenue loss and even potential job loss if disruptions become regular and significant enough. The impacts of climate change on supply chains include not only disruption to systems and additional costs associated with the transportation of goods but also potential health impacts to workers in industries that require working outdoors, such as agriculture,[325] fisheries, construction, and last-mile delivery,[328,329] who may be exposed to extreme heat or cold. Workers in these jobs may require additional heating or cooling or adjustments in shift times to avoid exposure to adverse weather conditions (KM 22.2; Ch. 19).[330]

## Expected Impacts of an Unplanned Calcasieu Navigation Lock Closure

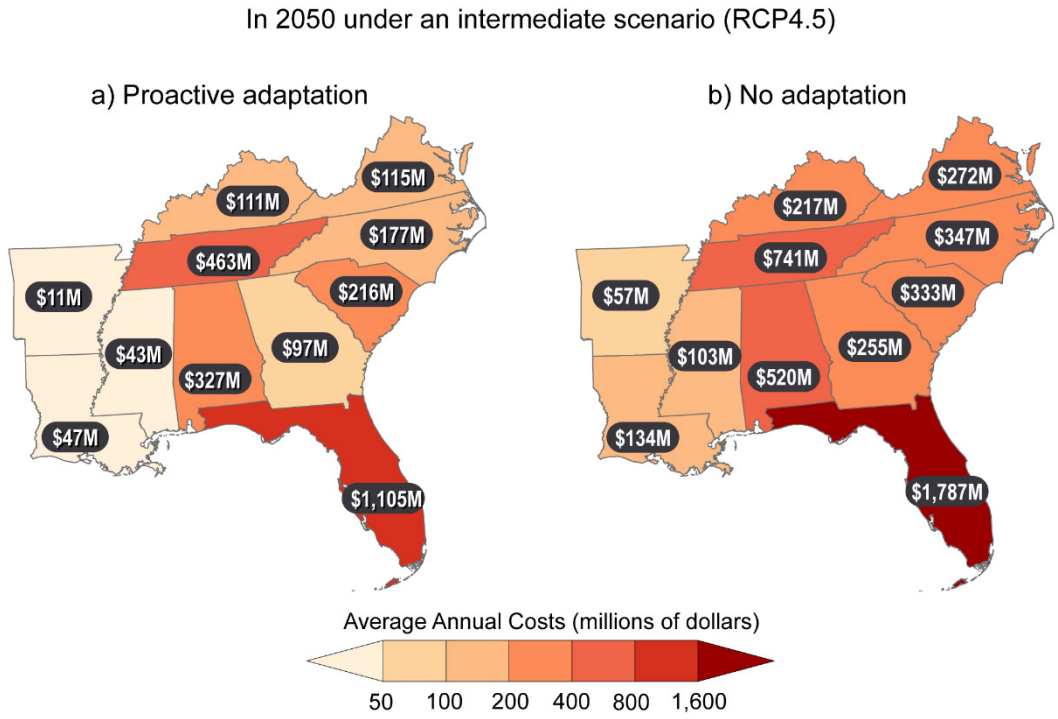



**An unplanned closure of the Calcasieu Navigation Lock would have impacts that extend well beyond the Southeast.**

**Figure 22.16.** The commodity flow impacts associated with an unplanned shutdown of Calcasieu Lock extend well outside the Southeast, affecting 170 counties across 18 states. Weather and climate extremes such as regional drought and low-flow conditions on the Mississippi River can result in unplanned shutdowns of the Calcasieu Lock. Adapted with permission from Burton et al. 2017.[315]

Furthermore, the Southeast is a hub of activity for oil refineries that provide fuel to the eastern half of the United States.[331] Climate change is expected to negatively impact not only refineries that are located along the Gulf Coast but also the distribution networks of the petroleum products that many rely on for emergency services, backup power generation, air travel, and more.[60,332,333]

## Projected Annual Energy Infrastructure Costs




**Proactively investing in strengthening our electrical infrastructure offsets significant future costs due to climate change damage.**

**Figure 22.17.** The Southeast faces some of the highest economic risks related to energy infrastructure damage without proactive adaptation measures in place—such as energy utilities and policymakers' anticipating climate risks to electrical grid infrastructure and investing upfront in strengthening these systems in advance of any damages. As shown in the maps, in 2050 under an intermediate scenario (RCP4.5), proactive adaptation (**a**) could save as much as twice the total costs (in 2017 dollars) of no adaptation (**b**). These costs could be passed onto consumers. Adapted from Fant et al. 2020[320] [CC BY 4.0].

## *Securing Economic Vitality*

Protecting businesses and urban and rural infrastructure investments may require adopting a combination of adaptation measures (KM 22.1). However, to avoid unintended disparities in service provision, these infrastructure investments should consider the needs of frontline communities in their design criteria.[334] For instance, Charleston, South Carolina, has explored questions surrounding the appropriate selection of adaptation measures, including protection techniques such as a seawall versus a greater reliance on nature-based solutions.

Justly transitioning to a low-carbon economy provides opportunities for businesses[335] as well as labor,[336] assuming that marginalized populations and women are included in this workforce to avoid the inequities of our current energy labor markets.[337] Business and governmental agencies could commit to workforce programs for employees in the oil, gas, and coal-producing industries,[336,338] as workforce training in green technology must address challenges associated with transitioning away from economies that are closely tied to a community's way of life.[339,340] Additionally, ecosystem restoration and nature-based green infrastructure solutions (e.g., urban forestry, stormwater retention gardens, green roofs) may also provide meaningful job opportunities (Ch. 19).[341] Key to adapting to climate change and leveraging new opportunities is the need for training and workforce development, which will require investment and prioritization (Ch. 19).

## Key Message 22.4

## Agriculture Faces Growing Threats, but Innovations Offer Help

Changes in temperature, drought, extreme rainfall, and sea levels are already threatening the Southeast's agriculture and other food-related systems (*likely*, *very high confidence*). Moreover, these climate-related hazards are expected to worsen with every increment of global warming, disproportionately harm farmers and small-scale operations, and increase the competition between urban and rural communities for valuable resources such as water and land (*high confidence*, *very likely*). However, innovative agricultural techniques such as precision farming show promise for adapting to future climate changes in the region (*likely*, *high confidence*).

Agriculture is critical to the economy of the Southeast through its production of food and fiber and employment. In the United States as a whole, agriculture, food, and related industries contributed $1.26 trillion (in 2022 dollars; a 5.2% share) to the gross domestic product in 2019.[342] In the Southeast, nearly 500,000 farms produced market sales of more than $83.8 billion (in 2022 dollars),[343] and the region's agricultural products are consumed locally and exported throughout the United States and the world.[344] Food systems distribute agricultural products throughout the region, although food deserts are present in urban and rural areas.[345] Disparities in food distribution are especially pronounced in areas with concentrations of Black, Indigenous, and under-resourced communities.[345]

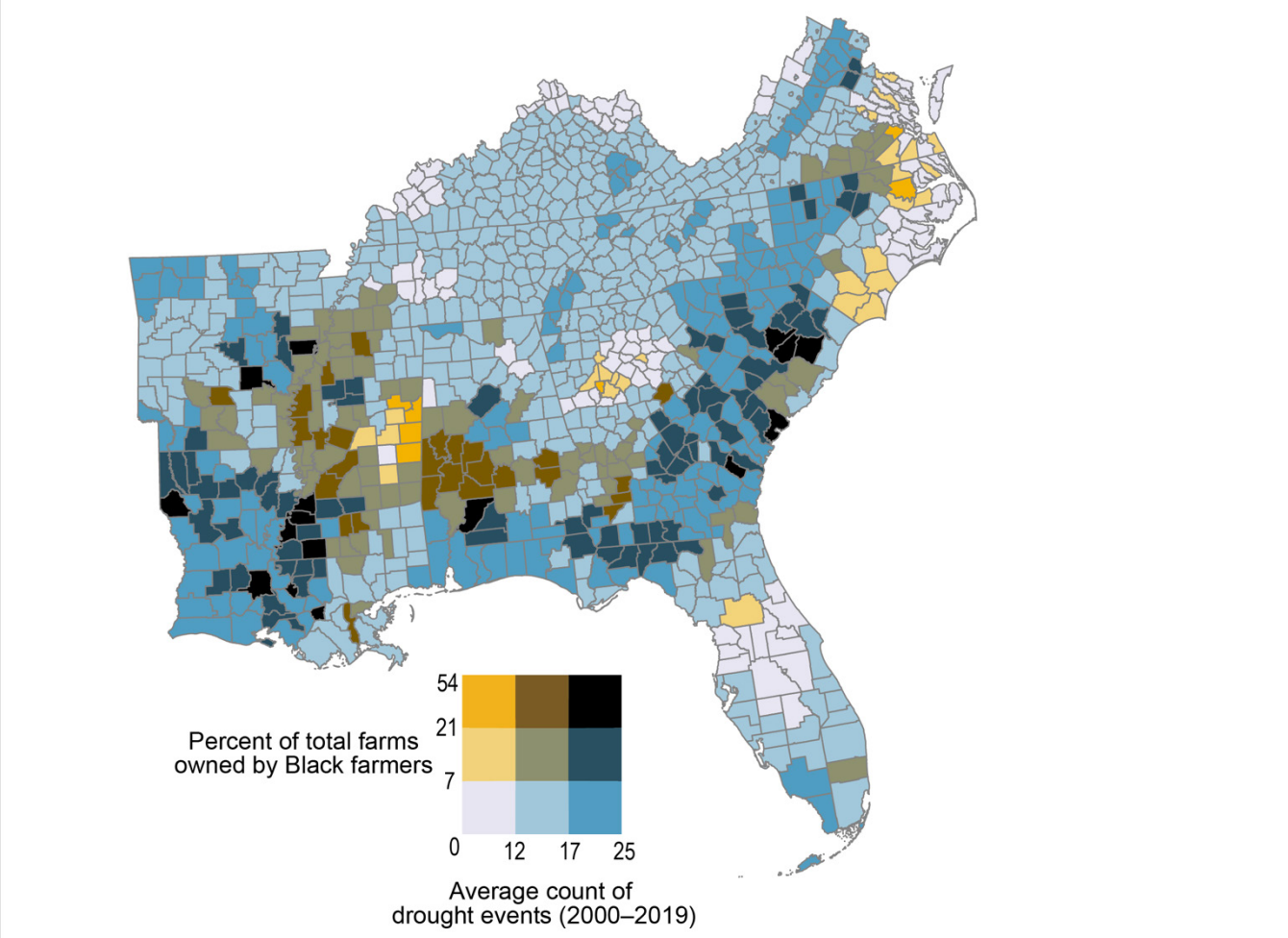
### *Climate Stressors on Agriculture and Food Systems*

Climate change stresses agriculture and food systems (Ch. 11). Threats from a changing climate include both direct threats through impacts of climate extremes on crops, forests, ecosystems, and livestock and indirect threats through impediments to transportation, the health of outdoor workers and animals, degradation and loss of natural ecosystems, reduced productivity and loss of traditional crops, increased threats from invasive species and weeds, and loss of livelihood for vulnerable communities such as rural BIPOC farmers. For example, increased average and extreme high temperatures[346] have led to increased heat stress on livestock[325,347] and outdoor workers. Warmer winter temperatures have reduced the number of chill hours (the total number of hours a plant experiences temperatures below 45°F over the winter months), which are essential for fruit production,[348] and have caused unusually early blooming of crops such as peaches and blueberries, which makes them vulnerable to damaging frost events. In spite of warmer winters, however, the change in the average date of the last spring frost is not consistent across the region.[349]

Higher temperatures, particularly overnight temperatures, have reduced crop yields,[350] and these impacts are projected to worsen with additional global warming (Figure 22.19; Ch. 11). They have also led to an increase in the occurrence of drought in the region (Figure 22.18).[351,352,353] The Southeast is the only region in the eastern half of the United States that is prone to extreme drought,[308] and flash droughts occur with higher frequency there than in any other region.[354] Longer-term droughts in the Southeast appear to be increasing in severity but do not appear to be occurring more frequently.[355] Changes in climate conditions have also contributed to increased pressure by invasive species that have resulted in crop yield losses and damaged productive natural ecosystems.[356,357] Increases in the frequency of heavy rain events[358] and lengthening of dry spells between rain events at some locations in the region[359,360,361] make water resources unpredictable. Hurricanes and tropical storm winds, as well as increasing accumulated rainfall in coastal areas, pose unique threats to agriculture.[92,362] For example, following Hurricane Florence, swine feces markers were detected in surface waters in North Carolina, suggesting that management practices should be examined in areas at risk of increased extreme precipitation.[363] Rising sea levels have increased saltwater intrusion in coastal aquifers, reducing the extent of available forests and farmland[130,131] and threatening

seafood harvesting in estuaries by altering the salinity and turbidity in freshwater streams and marine nurseries.[364] Extreme weather and coastal stressors have also disrupted food distribution by closing ports and highways,[365,366,367] reduced the catch of fish, and diminished crop production.[140]

### Droughts and Black Farmers in the Southeast




**The Southeast's Black farmers face disproportionate weather and climate risks.**

**Figure 22.18.** In the Southeast, areas with a higher number of drought events from 2000 through 2019 often overlapped with counties that are home to relatively higher proportions of Black producers, as identified in the 2017 USDA Census of Agriculture. The Southeast has the highest proportion of Black producers when compared to any other National Climate Assessment region, highlighting how disparities in climate risks require innovation and equitable adaptation, especially for those producers who have smaller operations and fewer resources to adopt new technologies. Figure credit: Groundwork USA, University of Georgia, NOAA NCEI, and CISESS NC.

## *Disproportionate Impacts on Under-Resourced Communities*

Climate stressors such as drought have a disproportionate impact on small-scale, Black, Indigenous, and economically disadvantaged farmers, who are more concentrated in the Southeast compared to other NCA regions (Figure 22.18).[368,369,370] These groups are under-resourced, making adaptation to climate change more difficult.[371] Knowledge gaps in best practices for small-farm management complicate information-sharing among communities across the region. Access to broadband in rural areas may limit producers' ability to monitor their fields and make appropriate management decisions.[372,373] Small-farm owners also have limited financial resources, which means they have less ability to invest in necessary farm equipment, insurance,

and other risk-reduction methods such as irrigation that could mitigate climate stress and reduce farmland value losses.[374,375] Small-scale farmers and those with limited resources may find targeted USDA programs as well as innovative techniques such as organic farming and agroforestry to be well-suited to use on their smaller farms in the future.[376,377]

## Competition for Resources

Southeastern agriculture and food systems are further stressed by land, water, and resource competition between urban and rural areas.[378] Competition is highlighted by decades of lawsuits in the Southeast involving the appropriate distribution of water resources among municipal water users in large cities, agricultural producers using irrigation to protect against drought, and coastal fisheries that rely on balanced salinity levels to maintain the health of estuarine systems.[379] Sprawl is expanding into farmland, reducing the land available for food production and increasing the area affected by urban heat islands.[380] Similarly, native forests have been developed or replaced by commercial forests, which may lack biodiversity and ecosystem resilience.[381]

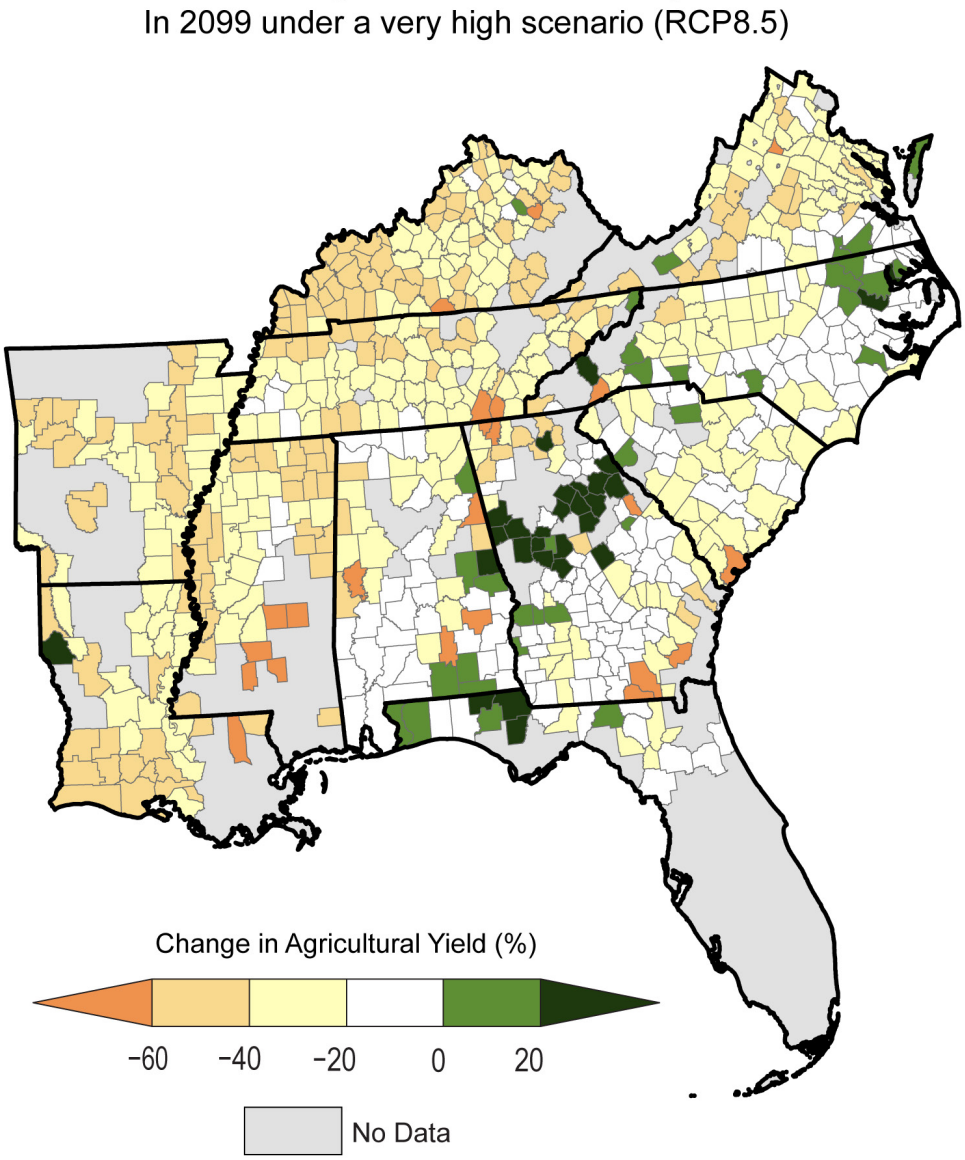
## Regional Dependencies

Climate stressors in other regions can have cascading effects on the Southeast and in turn the entire United States. For example, sea level rise is expected to hinder the operation of ports where food, other agricultural products, and other needed supplies are imported and exported (KM 22.3). Additionally, low and high flows from droughts and floods may hamper the movement of food and agricultural products within and through the region, especially in highly urban and rural areas.[382,383] Climate extremes can also reduce crop yields elsewhere and thus the availability of food products for the Southeast, potentially increasing stress on under-resourced populations through cost hikes and decreasing access to nutritious food.[384,385]

## How Agriculture and Food Systems Are Adapting in the Southeast

Agricultural producers are using various techniques to respond to increased climate stress, which is expected to result in decreased crop yields in many parts of the Southeast (Figure 22.19).[300] Precision agriculture can minimize water use through the timely and appropriate irrigation of crops based on growth stage and soil moisture.[386] The use of cover crops to preserve soil moisture and nutrients reduces the impacts of soil erosion and the leaching of nitrate into waterways and coastal estuaries, as well as the need for expensive inputs of fertilizer and irrigation water (Ch. 11).[387,388,389] Other innovative agricultural techniques such as organic farming, advanced grazing management, silvopasture, agroforestry, and other agroecological systems (Box 22.3) also show promise for adapting to future climate changes in the region through a reduction in emissions of greenhouse gases and increased carbon sequestration in the soil and vegetation.[376] New crops such as olives and satsuma citrus have been introduced to some areas to take advantage of the shifting plant hardiness zones and favorable market value of the crops.[390,391,392,393] Genetically modified organisms and new cultivars of perennial crops can contribute to reduced emissions of greenhouse gases through reductions in fieldwork and may reduce the need for inputs such as pesticides, as well as provide additional resilience to expected increases in temperature and drought that may threaten long-term yields.[394,395,396] A longer growing season also allows some producers to grow two crops in a year instead of one, reducing the likelihood of a weather catastrophe destroying a year's harvest in a single event.[397]

## Projected Changes in Agricultural Yields Under Unmitigated Climate Change




**Agricultural yields are expected to decrease under very high warming.**

**Figure 22.19.** Agricultural yields (area-weighted average for corn, wheat, soybeans, and cotton) in the Southeast are expected to decrease due to the warmer climate in the future by 2099 under a very high scenario (RCP8.5). Some areas, however, may see yield increases due to less severe climate changes in these places, as well as limited impacts due to sea level rise and tropical storm damage. Decreases in crop yield are expected to negatively impact regional and national food supplies while threatening agricultural lifestyles and traditions. Adapted from Hsiang et al. 2017.[300]

## Box 22.3. Indigenous Stewardship of Southeast Ecosystems: Rivercane

Rivercane (*Arundinaria gigantea*) is a Tribal cultural keystone species[398] and one of only three North American native bamboos. Once abundant and now critically endangered at just 2% of its original range, the species is still found throughout the Southeast.[399] Tribal Nations including the Cherokee, Chickasaw, Chitimacha, Choctaw, Houma, Koasati, and Seminole[400] value rivercane in cultural lifeways. It is used for food, textiles, basketry, medicine, weapons and hunting, and musical instruments. Many Tribal elders have a relationship with rivercane as a non-human relative.[401] Before settler colonialism, rivercane formed canebrakes, thickets of grasses that extended for miles, forming a feature from the South's deepest history.

Native peoples actively managed or tended canebrakes through consistent thinning to provide habitat and the required culms (stems) for cultural uses.[401] Canebrakes competed with European agriculture: cattle readily ate cane, particularly young shoots; pigs rooted for rhizomes,[402] killing the plant; and crops were planted where cane once thrived. Urbanization, removal of fire from the landscape as a management practice, overgrazing by cattle, and lack of public knowledge of rivercane's indigenousness have led to the plant's diminishment. The significantly reduced range of the rivercane is now further threatened by invasive species that are thriving under climate change.[403] Where it still exists, rivercane provides prime habitat for more than 50 animal species,[400] and at least six species require rivercane to complete their life cycles.[404]

Rivercane provides ecosystem benefits such as soil and water quality improvements and river and stream bank stabilization.[405] Rivercane produces seeds during rare mass fruiting events, the timing of which is unknown. For this reason, controlled reproduction has been limited and requires more research if the plant is to thrive in the future.[401] Current efforts are underway to restore rivercane, especially large swaths of canebrakes, as part of Tribal efforts to maintain sovereignty and cultural continuance.

> *I feel like we have to educate the public of Cherokee culture, foods, and artisan resources. It is not just rivercane affected by climate change, loss of habitat, and the public's lack of understanding of their cultural significance to our Tribal members, and other Tribes of the Southeast. — Mary W. Thompson, Eastern Band of Cherokee Indians*[406]

### Rivercane in North America

**Rivercane, a native bamboo, is culturally important to many Tribes in the Southeast.**

**Figure 22.20.** (**left**) Rivercane grows by the French Broad River in Buncombe County, North Carolina. (**right**) Basket weaver Ramses King (Mississippi Band of Choctaw Indians) creates a "double-weave" basket (2014). The significantly reduced range of rivercane, largely due to land cover changes and agriculture, is now further threatened by invasive species that are thriving under climate change. Photo credits: (left) © Adam Griffith, Revitalization of Traditional Cherokee Artisan Resources; (right) Lance Cheung, USDA.

# Traceable Accounts

## *Process Description*

Author selection for the Southeast chapter began with assessing the geographic distribution, career level, and academic expertise of the individuals listed in the Federal Register Notice nomination list. The chapter lead author (CL) then also assessed a number of other characteristics including demographics and previous experience with National Climate Assessment (NCA) chapter development. Initial invitations were sent following US Global Change Research Program (USGCRP) guidance. The CL extended multiple rounds of invitations until the final list of authors for the Zero Order Draft (ZOD) was complete in February 2022, achieving a distribution of career stages, expertise, and geographic representation. Additional authors were added after ZOD reviews from USGCRP agencies were assessed. Author team meetings were held virtually and were used primarily to gather consensus on the direction of the chapter content. In preparation for the public engagement workshops that were held in January and February 2022, the author team worked through the format of the engagement and how feedback would be gathered and summarized. The CL also gathered ZOD feedback from regionally focused organizations: the Southeast Sustainability Directors Network (January 18, 2022) and the Southeast and Caribbean Disaster Resilience Partnership (January 26, 2022), as well as a youth-focused event put on by the Youth Environmental Alliance in Higher Education (February 15, 2022).

Subsequent drafts of this report reflected changes and edits agreed upon by a simple majority of authors in response to several dozen comments and suggestions from public, National Academies, and USGCRP Agency reviews. Consensus on chapter-wide changes was usually unanimous, with very few changes needing considerable discussion. The largest changes to the chapter occurred during the drafting of the Fourth Order Draft (4OD), as this was the draft that would need to respond to a large number of public and National Academies comments. Many of the changes would be instituted during the All-Author Meeting in April 2023. Review Editor Tisha Holmes ratified that the changes satisfied all public and NASEM comments before submission of the 4OD for Technical Support Unit editorial review.

## Key Message 22.1

## Regional Growth Increases Climate Risks

### Description of Evidence Base

Population growth and land-use change in the Southeast have been widely reported on in a variety of contexts, including in previous NCAs. This evidence has only gotten more detailed since NCA4.[19]

The relationship between global warming and increases in regional sea level trends has recently been substantially improved, allowing for highly detailed descriptions of future relative sea level and thus flood risks.[51] Other advances related to projections of future rainfall intensity, duration, and frequency tied to both nontropical[100] and tropical systems[92] have greatly improved our understanding of future changes in the Southeast, including its potential downstream impacts on frontline communities.[13,53]

A wide body of quantitative research and qualitative practice has shown that the proactive adoption of risk reduction measures can significantly reduce future losses tied to natural hazards, including those exacerbated by a changing climate.[154] Furthermore, there is widespread agreement that natural hazards and climate change is disproportionately impacting socially vulnerable populations.[3] Planning and the distribution of funding have the potential to significantly reduce hazard risk, including that associated with climate change. However, the application of land-use planning techniques varies widely, and access to external grant funding is more often obtained by wealthier communities.[16,17]

### Major Uncertainties and Research Gaps

Projections of future population are based on many assumptions. Research on how future land-use change will exacerbate particular climate stressors in southeastern cities and across the region could help inform the best use of interventions and application of growth strategies. There have been limited analyses of adaptation activities in the Southeast, data inputs used, and evaluation of impacts. Downscaling global climate change models to inform geospatially targeted adaptation tools and techniques at the neighborhood and parcel scale is improving. However, the use of this downscaled information requires continued refinement to improve accuracy; in addition, better processes for sharing this information would help local officials, including low-wealth jurisdictions with limited staff and technical expertise. There still exists uncertainty regarding how future intensification of storms will impact design standards, such as determining the appropriate design standard in an era of climate change, who makes these decisions, and who pays for the additional costs. These questions apply to housing, public facilities, and infrastructure. It remains uncertain how well communities are reducing hazard risk when accounting for both individual projects (which have been captured effectively in terms of future losses avoided) and ongoing development, which includes a variety of standards, ordinances, and public investments. There is limited literature estimating sub-daily precipitation metric projections for the Southeast. The degree to which future land use and urbanization will exacerbate or overpower climate change–intensified risks at the local level, especially in frontline communities, is under-explored in the current literature.

### Description of Confidence and Likelihood

Population trends from the US Census Bureau are highly reliable through time and space, and as such, we ascribe *very high confidence* to reporting their data as well as future population estimates that virtually without exception agree on continued regional growth, warranting a *very likely* assessment. Risk management and assessment literature is extremely consistent on how sprawl and development relate to natural disaster risk, earning these statements *very high confidence* and *likely* assessments. That governance structures of varying scales are using outdated and/or limited information on climate-related risks is a well-reported feature within the flooding, disaster preparedness, and urban planning literature, so we assign *high confidence* to these statements. There is overwhelming consensus that climate adaptation efforts are concentrated in wealthier, more resourced communities, and therefore we assign assessments of *high confidence* and *likely*. There is overwhelming consensus that under-resourced, older, and marginalized communities are at higher and increasing risk from present and future climate extremes, although the risk in rural areas is less fully assessed quantitatively, thus resulting in our assignment of *high confidence* and *likely*.

## Key Message 22.2

## Climate Change Worsens Human Health and Widens Health Inequities

### Description of Evidence Base

There is strong evidence and consensus that climate change is already affecting the health and well-being of populations in the Southeast.[19] There is also strong evidence and consensus that climate-related environmental health stressors are projected to worsen.[19]

There is evidence that residents in the Southeast have poorer health in general compared to other US regions[196] and have limited access to healthcare resources.[202,288]

It is well established that there are preexisting inequities in health and healthcare access, safe and affordable housing, and access to resources to adapt to climate change, and that these inequities are associated with communities with a high proportion of under-resourced and BIPOC (Black, Indigenous, and People of Color) residents.[3,12,202,220]

The occurrence and projection of more frequent and intense extreme heat events are well documented by temperature models of the Southeast.[3,230,231] The literature assesses the disproportionate health impacts of heat on those most affected, including people who work outdoors,[212,213] student and nonstudent athletes,[214,215,216] and those who do not have adequate housing or cannot afford the energy costs of air-conditioning their homes.[218,220,222]

The literature outlines the causal pathway of how climate change is compromising air quality in the Southeast as a result of increasing favorable conditions for wildfires,[244,245,246,256,262] longer and more intense pollen seasons,[253,254,407] and increased production of smog,[241,242,243] as well as the subsequent health impacts. There is some evidence that warmer temperatures are associated with an increase in harmful algal bloom events,[267] which occur in fresh, brackish, and salt water, commonly occur in coastal areas in Florida, and can have detrimental effects on ecosystems, affecting plant, animal, and human health.[273]

The literature has established that climate change broadens the geographic distribution and season of certain disease-carrying mosquitoes and ticks, particularly in the Southeast, for tick-borne illnesses such as Lyme disease[281,282,283] and mosquito-borne illnesses such as West Nile virus and Zika virus.[284]

Mental health data have established that the Southeast ranks worst among all regions of the US in the prevalence of mental illness and access to mental health care services,[287,288] which is of particular concern as extreme weather events occur more frequently and intensely in the Southeast, causing displacement and stress.[293]

## Major Uncertainties and Research Gaps

The degree to which health will be affected by climate change and climate adaptations is uncertain, due to various compounding factors that can influence health effects. There are few studies that quantify the health impacts of climate adaptation interventions in the Southeast, so there is a limited understanding of effective public health strategies for addressing climate change.

Because there is limited data on pollen and vector-borne diseases in the Southeast, it is challenging to fully understand the impacts of climate change on these disease exposures.

There is also limited quantitative data on the mental health impacts of climate change. This information tends to rely on survey data, qualitative data, and anecdotal information.

## Description of Confidence and Likelihood

There is a high degree of agreement in the scientific literature that climate change will impact and is already impacting extreme temperature and precipitation events, air quality, water quality, the spread of vector-borne diseases, and the prevalence of algal blooms, all of which have an impact on the health of people in the Southeast, as evidenced by health outcome information including health impact assessments of recent events, health projections of future events, and environmental health trends in the Southeast. Based on this information, the authors assigned *very high confidence* that the changes in temperature and precipitation due to climate change, in conjunction with changes in air quality, water quality, the spread of vector-borne diseases, and the prevalence of algal blooms, will impact, and is *very likely* already impacting, the health and well-being of people in the Southeast.

It is well established that the conditions in which people live and work have an impact on health, which is understood as the social determinants of health. It is also well established by the literature and lived experience that marginalized populations will experience disproportionate health impacts, as that is seen consistently across public health and particularly in environmental health. For this reason, as well as because of the breadth of literature on the disproportionate impacts of climate change on the health of marginalized populations, the authors assigned *very high confidence* that community characteristics such as

racial and ethnic population, chronic disease prevalence, age, and socioeconomic status, can influence how climate change exacerbates, ameliorates, or introduces new health issues, widening the gap in health status.

Based on models of health impacts under varying climate scenarios, it is well-established that lower emission scenarios will result in less severe health outcomes. The literature is less established on the health benefits of climate adaptation efforts, as there is not a breadth of literature or evaluations on this topic, although from the literature that is available it is apparent that climate adaptation actions can improve health. For this reason, the authors assigned *high confidence* that climate mitigation and adaptation efforts can save lives and reduce the public health burden of climate change, particularly around reducing air pollutants and targeting already-marginalized communities, which is where the literature is more established.

## Key Message 22.3

## Climate Change Disproportionately Damages Southeastern Jobs, Households, and Economic Security

### Description of Evidence Base

There is a rapidly growing literature presenting both qualitative and quantitative evidence that livelihoods across the Southeast are already being impacted by climate change in a variety of important ways (Ch. 19),[298] including place-based economies such as construction, tourism, and agriculture and aquaculture (e.g., fisheries are being impacted not only by significant hurricanes but also by geographical shifts among species in ocean waters),[408,409] as well as systems like transportation infrastructure[317] and electrical grid infrastructure[320] that undergird the distribution of goods and services in these places. Extreme weather-related disruptions and adverse working conditions created by climate change can affect both people and infrastructure systems that support local and regional economies by impacting the local community as well as regional and global supply chains.[326,327] References and figures included in Chapter 19 were instrumental to establishing author team consensus around key statements related to economic impacts being relatively larger in the Southeast than in other NCA regions.

### Major Uncertainties and Research Gaps

Localized impacts on inland agriculture and tourism are not fully understood to date. The relocation of individuals and households away from climate-affected areas to other locations and their need to establish new livelihoods are not well understood, nor is the effectiveness of federal funding to support the construction of new settlements in less hazardous areas. The degree to which small and midsized businesses are adapting to climate change–related threats remains uncertain. The extent to which climate changes will impact large-scale agriculture is fairly well established, but the fiscal impact on small-scale family farms is not as well understood. There is limited research on the low-flow conditions and projections related to drought and its impacts on the Mississippi River and its tributaries as well as on the potential impacts to economies, despite how disruptive the events are to the regional, national, and global economy.

### Description of Confidence and Likelihood

Based on the author team consensus reached through evaluating the evidence base presented in the literature as well as through direct and related experience in recent extreme weather and climate events impacting the Southeast, the authors have assigned *high confidence* to the statements surrounding the concentration of economic growth in urban centers, the climate-related risks to place-based economies that rely on ecosystems and to southeastern economies and labor, and the need for coordinated strategies

to prepare for the shocks and stressors of the future. *Medium confidence* was assigned to the evaluation of the extent to which urban centers depend on the interregional connections to more rural places and other urban centers due to limited peer-reviewed literature in this area. While there are reports and white papers on this subject from nonprofits and research think tanks that largely agree on the potential for disruptions to these systems to have impacts on both rural and urban centers, limited peer-reviewed studies seeking to isolate urban/rural dependencies in the face of climate change support at least *medium confidence*. Projections of future climate impacts in the Southeast are particularly robust in their evaluation of future heat and extreme precipitation risks; we assign *very likely* and *high confidence* to our Key Message statements that seek to link climate impacts to economic outcomes in the Southeast. Chapter 19 (Economics) was especially helpful in establishing our *very likely* and *high confidence* assessments.

## Key Message 22.4

## Agriculture Faces Growing Threats, but Innovations Offer Help

### Description of Evidence Base

Evidence of trends in temperature, precipitation, and growing season are well documented in sources such as the NOAA National Centers for Environmental Information's Climate at a Glance Tool and in the scientific literature.[346,350] This literature base is extensive and covers individual states, the Southeast region, the United States, and the globe. Earlier concerns about temperature trends from satellite observations, which did not match surface-based observations, have largely been resolved by improved calibration of satellite measurements.

Trends in precipitation show changes in both amount and temporal and spatial distribution that are more difficult to separate out due to the nature of precipitation in the Southeast and its ties to sub-grid-scale processes like convection and tropical systems.[358,359,360,361] Evidence of trends in drought are less certain because of the combination of interacting contributions from temperature, precipitation variability, and soil characteristics, but are becoming more apparent in recent modeling efforts that are documented in the scientific literature.[351,352]

The impacts of climate variability and change on agricultural production have been well documented in the scientific literature in agricultural journals in recent years.[350,356] More work is ongoing as better methods for collecting in-field measurements are used to fine-tune the relationships between plant physiology and climate variables.

The assessment of the impacts of climate change on the health of workers and livestock, transportation pathways for agricultural production, and economic losses to both large-production farmers and small BIPOC farming communities has increased greatly in the last four years and is being reported in scientific journal articles in health, infrastructure, economic, and other social science–oriented journals.[325,347]

Many examples of agricultural producers implementing climate adaptation in farming exist, suggesting a willingness to address the impacts of a changing climate across diverse land ownerships.

### Major Uncertainties and Research Gaps

There is significant uncertainty regarding the ability of crop species to keep pace with changes in climate (based on temperature and precipitation), although plant breeders have a long history of producing new hybrids that can improve responses to changing climate conditions. The ability of new crops to be productive in an altered climate is also uncertain due to concurrent changes in temperature, precipitation,

humidity, and soil characteristics, which interact with plant growth patterns. This leads to considerable uncertainty in the extent to which changes in crop choice and management can adapt to the future climate.

There is also uncertainty in the knowledge of carbon interactions between soils and crops, but numerous studies are underway to better document these interactions to improve future predictions.[376]

Since agriculture is a global endeavor, changes in market pricing and availability of inputs such as fertilizer, as well as outputs such as crop variety and yield, interact in a way that hinders the prediction of future agricultural outputs, droughts, and the economic effects of agricultural sales.[410] As a result, economic impacts on both large-scale farmers and economically disadvantaged farmers with small-scale operations are difficult to predict with *high confidence*.

## Description of Confidence and Likelihood

Based on the high degree of agreement in agricultural and climate science journal articles in the scientific literature and assessments of recent events, there is *very high confidence* that the interactions of warming temperatures, precipitation changes, sea level, and drought with insect pests, invasive plants, and plant pathogens are already threatening the region's agriculture and food-related systems and will *likely* lead to decreased yields of many crops and production of other agricultural goods.[356,357] Evaluations of recent past storm events coupled with the strong agreement in related journal articles resulted in an assignment of *very high confidence* that rising sea levels and impacts from tropical storms will disrupt coastal and port activities.[325,347] Studies by social scientists published in the literature also demonstrate that small-scale BIPOC producers, as well as those who have limited financial resources, will be disproportionately affected by climate-related hazards;[366,367] on that basis, the authors have described this as *very likely* with *high confidence* in the expected impacts. Additionally, based on examples in the scientific literature of adaptations that producers are already making in response to changes in the climate, the authors assigned a level of *high confidence* that producers in the Southeast will be able to adapt to those changes using techniques such as precision agriculture, changes in crop type, and innovative management of fisheries, livestock, and ecosystems, and a likelihood level of *likely* was assigned based on less agreement in the scientific literature about the degree to which they will be able to do so.[386,390,394]

# References


1. Aaronson, D., J. Faber, D. Hartley, B. Mazumder, and P. Sharkey, 2021: The long-run effects of the 1930s HOLC "redlining" maps on place-based measures of economic opportunity and socioeconomic success. *Regional Science and Urban Economics*, **86**, 103622. https://doi.org/10.1016/j.regsciurbeco.2020.103622

2. Davies, I.P., R.D. Haugo, J.C. Robertson, and P.S. Levin, 2018: The unequal vulnerability of communities of color to wildfire. *PLoS ONE*, **13** (11), 0205825. https://doi.org/10.1371/journal.pone.0205825

3. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

4. Gonzalez, D.J.X., A. Nardone, A.V. Nguyen, R. Morello-Frosch, and J.A. Casey, 2023: Historic redlining and the siting of oil and gas wells in the United States. *Journal of Exposure Science & Environmental Epidemiology*, **33** (1), 76–83. https://doi.org/10.1038/s41370-022-00434-9

5. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. https://doi.org/10.3390/cli8010012

6. Holifield, R., 2023: American landscapes of environmental injustice. In: *The Routledge Companion to the American Landscape*. Post, C.W., A.L. Greiner, and G.L. Buckley, Eds. Taylor & Francis, 10. https://doi.org/10.4324/9781003121800-8

7. KC, B., J.M. Shepherd, and C.J. Gaither, 2015: Climate change vulnerability assessment in Georgia. *Applied Geography*, **62**, 62–74. https://doi.org/10.1016/j.apgeog.2015.04.007

8. Lane, H.M., R. Morello-Frosch, J.D. Marshall, and J.S. Apte, 2022: Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environmental Science & Technology Letters*, **9** (4), 345–350. https://doi.org/10.1021/acs.estlett.1c01012

9. Lee, E.K., G. Donley, T.H. Ciesielski, I. Gill, O. Yamoah, A. Roche, R. Martinez, and D.A. Freedman, 2022: Health outcomes in redlined versus non-redlined neighborhoods: A systematic review and meta-analysis. *Social Science & Medicine*, **294**, 114696. https://doi.org/10.1016/j.socscimed.2021.114696

10. Liu, J., L.P. Clark, M.J. Bechle, A. Hajat, S.Y. Kim, A.L. Robinson, L. Sheppard, A.A. Szpiro, and J.D. Marshall, 2021: Disparities in air pollution exposure in the United States by race/ethnicity and income, 1990–2010. *Environmental Health Perspectives*, **129** (12), 127005. https://doi.org/10.1289/ehp8584

11. O'Connell, H.A., 2012: The impact of slavery on racial inequality in poverty in the contemporary U.S. South. *Social Forces*, **90** (3), 713–734. https://doi.org/10.1093/sf/sor021

12. Shepherd, M. and B. KC, 2015: Climate change and African Americans in the USA. *Geography Compass*, **9** (11), 579–591. https://doi.org/10.1111/gec3.12244

13. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

14. Jurjonas, M., E. Seekamp, L. Rivers, and B. Cutts, 2020: Uncovering climate (in)justice with an adaptive capacity assessment: A multiple case study in rural coastal North Carolina. *Land Use Policy*, **94**, 104547. https://doi.org/10.1016/j.landusepol.2020.104547

15. Ueland, J. and B. Warf, 2006: Racialized topographies: Altitude and race in southern cities. *Geographical Review*, **96** (1), 50–78. https://doi.org/10.1111/j.1931-0846.2006.tb00387.x

16. Smith, G. and O. Vila, 2020: A national evaluation of state and territory roles in hazard mitigation: Building local capacity to implement FEMA hazard mitigation assistance grants. *Sustainability*, **12** (23), 10013. https://doi.org/10.3390/su122310013

17. Vilá, O., G. Smith, B. Cutts, S. Gyawali, and S. Bhattarai, 2022: Equity in FEMA hazard mitigation assistance programs: The role of state hazard mitigation officers. *Environmental Science & Policy*, **136**, 632–641. https://doi.org/10.1016/j.envsci.2022.07.027

18. Cain, C., 2021: Ch. 33. Developing climatic capacity in rural places. In: *Investing In Rural Prosperity*. Dumont, A. and D.P. Davis, Eds. Federal Reserve Bank of St. Louis, 475–486. https://www.stlouisfed.org/-/media/project/frbstl/stlouisfed/files/pdfs/community-development/investing-rural/chapters/chapter33.pdf

19. Carter, L.M., A. Terando, K. Dow, K. Hiers, K.E. Kunkel, A. Lascurain, D.C. Marcy, M.J. Osland, and P.J. Schramm, 2018: Ch. 19. Southeast. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 743–808. https://doi.org/10.7930/nca4.2018.ch19

20. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

21. Whyte, K., 2018: Ch. 16. Food sovereignty, justice, and Indigenous peoples: An essay on settler colonialism and collective continuance. In: *The Oxford Handbook of Food Ethics*. Barnhill, A., M. Budolfson, and T. Doggett, Eds. Oxford University Press, 345–366. https://doi.org/10.1093/oxfordhb/9780199372263.013.34

22. Whyte, K.P., 2013: Justice forward: Tribes, climate adaptation and responsibility. *Climatic Change*, **120** (3), 517–530. https://doi.org/10.1007/s10584-013-0743-2

23. Emanuel, R.E., 2018: Climate change in the Lumbee River watershed and potential impacts on the Lumbee Tribe of North Carolina. *Journal of Contemporary Water Research & Education*, **163** (1), 79–93. https://doi.org/10.1111/j.1936-704x.2018.03271.x

24. Emanuel, R., L. Rivers, B. Cutts, and G. Blank, 2020: Data Analytics for Environmental Justice and Indigenous Rights: Early Warning Systems or Blind Spots? Earth and Space Science Open Archive. https://doi.org/10.1002/essoar.10501690.1

25. Emanuel, R.E., 2017: Flawed environmental justice analyses. *Science*, **357** (6348), 260–260. https://doi.org/10.1126/science.aao2684

26. Redvers, N., Y. Celidwen, C. Schultz, O. Horn, C. Githaiga, M. Vera, M. Perdrisat, L. Mad Plume, D. Kobei, M.C. Kain, A. Poelina, J.N. Rojas, and B.S. Blondin, 2022: The determinants of planetary health: An Indigenous consensus perspective. *The Lancet Planetary Health*, **6** (2), 156–163. https://doi.org/10.1016/s2542-5196(21)00354-5

27. Bartels, W.-L., C.A. Furman, D.C. Diehl, F.S. Royce, D.R. Dourte, B.V. Ortiz, D.F. Zierden, T.A. Irani, C.W. Fraisse, and J.W. Jones, 2013: Warming up to climate change: A participatory approach to engaging with agricultural stakeholders in the Southeast US. *Regional Environmental Change*, **13** (1), 45–55. https://doi.org/10.1007/s10113-012-0371-9

28. Buckley, G.A. and M.M. Moore-Driskell, 2021: Challenges in teaching climate science literacy in Alabama, Part I: Climate change and the Southeast U.S. warming hole. *Journal of Sustainability Studies*, **2** (1). https://ir.una.edu/work/ns/9825ae03-4f07-414b-a81b-ee4d92b71867

29. Lee, H., K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W.W.L.C. Cheung, S.L. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones, F. Jotzo, T. Krug, R. Lasco, J.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F.E.L. Otto, M. Pathak, A. Pirani, E. Poloczanska, H.-O. Pörtner, A. Revi, D.C. Roberts, J. Roy, A.C. Ruane, J. Skea, P.R. Shukla, R. Slade, A. Slangen, Y. Sokona, A.A. Sörensson, M. Tignor, D. van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, and Z. Zommers, 2023: Summary for policymakers. In: *Synthesis Report of the IPCC Sixth Assessment Report*. Arias, P., M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez, J. Pereira, R. Pichs-Madruga, S.K. Rose, Y. Saheb, R. Sánchez, D. Ürge-Vorsatz, C. Xiao, and N. Yassaa, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_SPM.pdf

30. McNeal, K.S., J.K.L. Hammerman, J.A. Christiansen, and F.J. Carroll, 2014: Climate change education in the southeastern U.S. through public dialogue: Not just preaching to the choir. *Journal of Geoscience Education*, **62** (4), 631–644. https://doi.org/10.5408/13-061.1

31. Monroe, M.C., A. Oxarart, and R.R. Plate, 2013: A role for environmental education in climate change for secondary science educators. *Applied Environmental Education & Communication*, **12** (1), 4–18. https://doi.org/10.1080/1533015x.2013.795827

32. Panos, A. and M.B. Sherry, 2023: Ch. 7. Storying climate change: Discursive possibilities for teaching climate justice literacies. In: *Critical Perspectives on Global Literacies: Bridging Research and Practice*. Kerkhoff, S.N. and H.A. Spires, Eds. Routledge, 124–139. https://doi.org/10.4324/9781003320142

33. Stewart, H. 2022: Co-Developing Climate-Smart Strategies: Enhancing Resiliency Among Alabama Row Crop Producers and Agricultural Stakeholders. Master of Science in Rural Sociology, Auburn University. https://etd.auburn.edu//handle/10415/8323

34. Rudd, M.A., A.F.P. Moore, D. Rochberg, L. Bianchi-Fossati, M.A. Brown, D. D'Onofrio, C.A. Furman, J. Garcia, B. Jordan, J. Kline, L.M. Risse, P.L. Yager, J. Abbinett, M. Alber, J.E. Bell, C. Bhedwar, K.M. Cobb, J. Cohen, M. Cox, M. Dormer, N. Dunkley, H. Farley, J. Gambill, M. Goldstein, G. Harris, M. Hopkinson, J.-A. James, S. Kidd, P. Knox, Y. Liu, D.C. Matisoff, M.D. Meyer, J.D. Mitchem, K. Moore, A.J. Ono, J. Philipsborn, K.M. Sendall, F. Shafiei, M. Shepherd, J. Teebken, and A.N. Worley, 2018: Climate research priorities for policy-makers, practitioners, and scientists in Georgia, USA. *Environmental Management*, **62** (2), 190–209. https://doi.org/10.1007/s00267-018-1051-4

35. Meerow, S. and L. Keith, 2022: Planning for extreme heat. *Journal of the American Planning Association*, **88** (3), 319–334. https://doi.org/10.1080/01944363.2021.1977682

36. Sobel, R.S. and P.T. Leeson, 2006: Government's response to Hurricane Katrina: A public choice analysis. *Public Choice*, **127** (1), 55–73. https://doi.org/10.1007/s11127-006-7730-3

37. Crowley, J., 2021: Social vulnerability factors and reported post-disaster needs in the aftermath of Hurricane Florence. *International Journal of Disaster Risk Science*, **12** (1), 13–23. https://doi.org/10.1007/s13753-020-00315-5

38. Shultz, J.M., E.J. Trapido, J.P. Kossin, C. Fugate, L. Nogueira, A. Apro, M. Patel, V.J. Torres, C.K. Ettman, Z. Espinel, and S. Galea, 2022: Hurricane Ida's impact on Louisiana and Mississippi during the COVID-19 Delta surge: Complex and compounding threats to population health. *The Lancet Regional Health - Americas*, **12**, 100286. https://doi.org/10.1016/j.lana.2022.100286

39. Sanders, M.C., 2021: Equity in addressing climate change: Using law and policy to serve frontline communities. *Traumatology*, **27**, 48–51. https://doi.org/10.1037/trm0000284

40. U.S. Census Bureau, 2021: Race and Ethnicity in the United States: 2010 Census and 2020 Census. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/library/visualizations/interactive/race-and-ethnicity-in-the-united-state-2010-and-2020-census.html

41. Jiang, L., B.C. O'Neill, H. Zoraghein, and S. Dahlke, 2020: Population scenarios for U.S. states consistent with Shared Socioeconomic Pathways. *Environmental Research Letters*, **15** (9), 094097. https://doi.org/10.1088/1748-9326/aba5b1

42. Nowak, D.J. and E.J. Greenfield, 2018: US urban forest statistics, values, and projections. *Journal of Forestry*, **116** (2), 164–177. https://doi.org/10.1093/jofore/fvx004

43. Hamilton, H., R.L. Smyth, B.E. Young, T.G. Howard, C. Tracey, S. Breyer, D.R. Cameron, A. Chazal, A.K. Conley, C. Frye, and C. Schloss, 2022: Increasing taxonomic diversity and spatial resolution clarifies opportunities for protecting US imperiled species. *Ecological Applications*, **32** (3), e2534. https://doi.org/10.1002/eap.2534

44. Strader, S.M., 2018: Spatiotemporal changes in conterminous US wildfire exposure from 1940 to 2010. *Natural Hazards*, **92** (1), 543–565. https://doi.org/10.1007/s11069-018-3217-z

45. Freeman, A.C. and W.S. Ashley, 2017: Changes in the US hurricane disaster landscape: The relationship between risk and exposure. *Natural Hazards*, **88** (2), 659–682. https://doi.org/10.1007/s11069-017-2885-4

46. Ferguson, A.P. and W.S. Ashley, 2017: Spatiotemporal analysis of residential flood exposure in the Atlanta, Georgia metropolitan area. *Natural Hazards*, **87** (2), 989–1016. https://doi.org/10.1007/s11069-017-2806-6

47. Ashley, W.S., A.M. Haberlie, and V.A. Gensini, 2023: The future of supercells in the United States. *Bulletin of the American Meteorological Society*, **104** (1), E1–E21. https://doi.org/10.1175/bams-d-22-0027.1

48. Strader, S.M., W.S. Ashley, T.J. Pingel, and A.J. Krmenec, 2017: Observed and projected changes in United States tornado exposure. *Weather, Climate, and Society*, **9** (2), 109–123. https://doi.org/10.1175/wcas-d-16-0041.1

49. U.S. Census Bureau, 2019: Coastline America. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/library/visualizations/2019/demo/coastline-america.html

50. Collins, E.L., G.M. Sanchez, A. Terando, C.C. Stillwell, H. Mitasova, A. Sebastian, and R.K. Meentemeyer, 2022: Predicting flood damage probability across the conterminous United States. *Environmental Research Letters*, **17** (3), 034006. https://doi.org/10.1088/1748-9326/ac4f0f

51. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

52. Thompson, P.R., M.J. Widlansky, B.D. Hamlington, M.A. Merrifield, J.J. Marra, G.T. Mitchum, and W. Sweet, 2021: Rapid increases and extreme months in projections of United States high-tide flooding. *Nature Climate Change*, **11** (7), 584–590. https://doi.org/10.1038/s41558-021-01077-8

53. Titus, J.G., 2023: Population in floodplains or close to sea level increased in US but declined in some counties—Especially among black residents. *Environmental Research Letters*, **18** (3), 034001. https://doi.org/10.1088/1748-9326/acadf5

54. Smith, A.B. 2020: U.S. Billion-dollar Weather and Climate Disasters, 1980 - Present. National Oceanic and Atmospheric Administration, National Centers for Environmental Information. https://doi.org/10.25921/stkw-7w73

55. Howe, P.D., M. Mildenberger, J.R. Marlon, and A. Leiserowitz, 2015: Geographic variation in opinions on climate change at state and local scales in the USA. *Nature Climate Change*, **5** (6), 596–603. https://doi.org/10.1038/nclimate2583

56. Marlon, J., L. Neyens, M. Jefferson, P. Howe, M. Mildenberger, and A. Leiserowitz, 2022: Yale Climate Opinion Maps 2021. Yale Program on Climate Change Communication. https://climatecommunication.yale.edu/visualizations-data/ycom-us/

57. Richardson, J., B. Mitchell, and J. Franco, 2019: Shifting Neighborhoods: Gentrification and Cultural Displacement in American Cities. National Community Reinvestment Coalition. https://ncrc.org/gentrification/

58. Wilbanks, T.J. and R.W. Kates, 2010: Beyond adapting to climate change: Embedding adaptation in responses to multiple threats and stresses. *Annals of the Association of American Geographers*, **100** (4), 719–728. https://doi.org/10.1080/00045608.2010.500200

59. Jufri, F.H., V. Widiputra, and J. Jung, 2019: State-of-the-art review on power grid resilience to extreme weather events: Definitions, frameworks, quantitative assessment methodologies, and enhancement strategies. *Applied Energy*, **239**, 1049–1065. https://doi.org/10.1016/j.apenergy.2019.02.017

60. Schaeffer, R., A.S. Szklo, A.F. Pereira de Lucena, B.S. Moreira Cesar Borba, L.P. Pupo Nogueira, F.P. Fleming, A. Troccoli, M. Harrison, and M.S. Boulahya, 2012: Energy sector vulnerability to climate change: A review. *Energy*, **38** (1), 1–12. https://doi.org/10.1016/j.energy.2011.11.056

61. DOT, 2019: Rural Public Transportation Systems. U.S. Department of Transportation, Washington, DC. https://www.transportation.gov/mission/health/Rural-Public-Transportation-Systems

62. Gutierrez, K.S. and C.E. LePrevost, 2016: Climate justice in rural southeastern United States: A review of climate change impacts and effects on human health. *International Journal of Environmental Research and Public Health*, **13** (2), 189. https://doi.org/10.3390/ijerph13020189

63. Hendricks, M.D. and S. Van Zandt, 2021: Unequal protection revisited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. *Environmental Justice*, **14** (2), 87–97. https://doi.org/10.1089/env.2020.0054

64. Hernandez, P., B. Daigle, T. Preston, K. Pohl, K. Smith, B. Powell, and S. Story, 2022: A Rural Capacity Map. Headwaters Economics, Bozeman, MT. https://headwaterseconomics.org/equity/rural-capacity-map/

65. Allen, M., L. Gillespie-Marthaler, M. Abkowitz, and J. Camp, 2020: Evaluating flood resilience in rural communities: A case-based assessment of Dyer County, Tennessee. *Natural Hazards*, **101** (1), 173–194. https://doi.org/10.1007/s11069-020-03868-2

66. Allen, T., J. Behr, A. Bukvic, R.S.D. Calder, K. Caruson, C. Connor, C. D'Elia, D. Dismukes, R. Ersing, R. Franklin, J. Goldstein, J. Goodall, S. Hemmerling, J. Irish, S. Lazarus, D. Loftis, M. Luther, L. McCallister, K. McGlathery, M. Mitchell, W. Moore, C.R. Nichols, K. Nunez, M. Reidenbach, J. Shortridge, R. Weisberg, R. Weiss, L.D. Wright, M. Xia, K. Xu, D. Young, G. Zarillo, and J.C. Zinnert, 2021: Anticipating and adapting to the future impacts of climate change on the health, security and welfare of low elevation coastal zone (LECZ) communities in southeastern USA. *Journal of Marine Science and Engineering*, **9** (11), 1196. https://doi.org/10.3390/jmse9111196

67. Kunkel, K.E., S.E. Stevens, L.E. Stevens, and T.R. Karl, 2020: Observed climatological relationships of extreme daily precipitation events with precipitable water and vertical velocity in the contiguous United States. *Geophysical Research Letters*, **47** (12), 2019GL086721. https://doi.org/10.1029/2019gl086721

68. Neupane, B., T.M. Vu, and A.K. Mishra, 2020: Evaluation of land-use, climate change, and low-impact development practices on urban flooding. *Hydrological Sciences Journal*, **65** (S3), 1729–1742. https://doi.org/10.1080/02626667.2021.1954650

69. Chakraborty, J., W. Collins Timothy, C. Montgomery Marilyn, and E. Grineski Sara, 2014: Social and spatial inequities in exposure to flood risk in Miami, Florida. *Natural Hazards Review*, **15** (3), 04014006. https://doi.org/10.1061/(asce)nh.1527-6996.0000140

70. Collins, T.W., S.E. Grineski, J. Chakraborty, and A.B. Flores, 2019: Environmental injustice and Hurricane Harvey: A household-level study of socially disparate flood exposures in Greater Houston, Texas, USA. *Environmental Research*, **179**, 108772. https://doi.org/10.1016/j.envres.2019.108772

71. Tate, E., M.A. Rahman, C.T. Emrich, and C.C. Sampson, 2021: Flood exposure and social vulnerability in the United States. *Natural Hazards*, **106** (1), 435–457. https://doi.org/10.1007/s11069-020-04470-2

72. Knutson, T.R. and F. Zeng, 2018: Model assessment of observed precipitation trends over land regions: Detectable human influences and possible low bias in model trends. *Journal of Climate*, **31** (12), 4617–4637. https://doi.org/10.1175/jcli-d-17-0672.1

73. Khajehei, S., A. Ahmadalipour, W. Shao, and H. Moradkhani, 2020: A place-based assessment of flash flood hazard and vulnerability in the contiguous United States. *Scientific Reports*, **10** (1), 1–12. https://doi.org/10.1038/s41598-019-57349-z

74. FEMA, 2022: Flood Risk Disclosure: Model State Requirements for Disclosing Flood Risk During Real Estate Transactions. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_state-flood-risk-disclosure-best-practices_07142022.pdf

75. Harvard Joint Center for Housing Studies, 2022: America's Rental Housing 2022. Harvard University. https://www.jchs.harvard.edu/americas-rental-housing-2022

76. Bathi, J.R. and H.S. Das, 2016: Vulnerability of coastal communities from storm surge and flood disasters. *International Journal of Environmental Research and Public Health*, **13** (2), 239. https://doi.org/10.3390/ijerph13020239

77. Kusenbach, M., J.L. Simms, and G.A. Tobin, 2010: Disaster vulnerability and evacuation readiness: Coastal mobile home residents in Florida. *Natural Hazards*, **52** (1), 79–95. https://doi.org/10.1007/s11069-009-9358-3

78. Emrich, C.T., S.K. Aksha, and Y. Zhou, 2022: Assessing distributive inequities in FEMA's disaster recovery assistance fund allocation. *International Journal of Disaster Risk Reduction*, **74**, 102855. https://doi.org/10.1016/j.ijdrr.2022.102855

79. Thomson, H., H.B. Zeff, R. Kleiman, A. Sebastian, and G.W. Characklis, 2023: Systemic financial risk arising from residential flood losses. *Earth's Future*, **11** (4), e2022EF003206. https://doi.org/10.1029/2022ef003206

80. Wilson, B., E. Tate, and C.T. Emrich, 2021: Flood recovery outcomes and disaster assistance barriers for vulnerable populations. *Frontiers in Water*, **3**, 752307. https://doi.org/10.3389/frwa.2021.752307

81. Gourevitch, J.D., C. Kousky, Y. Liao, C. Nolte, A.B. Pollack, J.R. Porter, and J.A. Weill, 2023: Unpriced climate risk and the potential consequences of overvaluation in US housing markets. *Nature Climate Change*, **13** (3), 250–257. https://doi.org/10.1038/s41558-023-01594-8

82. Chew, G.L., J. Wilson, F.A. Rabito, F. Grimsley, S. Iqbal, T. Reponen, M.L. Muilenberg, P.S. Thorne, D.G. Dearborn, and R.L. Morley, 2006: Mold and endotoxin levels in the aftermath of Hurricane Katrina: A pilot project of homes in New Orleans undergoing renovation. *Environmental Health Perspectives*, **114** (12), 1883–1889. https://doi.org/10.1289/ehp.9258

83. Ebi, K.L., J. Vanos, J.W. Baldwin, J.E. Bell, D.M. Hondula, N.A. Errett, K. Hayes, C.E. Reid, S. Saha, J. Spector, and P. Berry, 2021: Extreme weather and climate change: Population health and health system implications. *Annual Review of Public Health*, **42** (1), 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

84. Vorhees, L., J. Harrison, M. O'Driscoll, C. Humphrey, and J. Bowden, 2022: Climate change and onsite wastewater treatment systems in the coastal Carolinas: Perspectives from wastewater managers. *Weather, Climate, and Society*, **14** (4), 1287–1305. https://doi.org/10.1175/wcas-d-21-0192.1

85. Paterson, D.L., H. Wright, and P.N.A. Harris, 2018: Health risks of flood disasters. *Clinical Infectious Diseases*, **67** (9), 1450–1454. https://doi.org/10.1093/cid/ciy227

86. Ramesh, B., M.A. Jagger, B. Zaitchik, K.N. Kolivras, S. Swarup, L. Deanes, and J.M. Gohlke, 2021: Emergency department visits associated with satellite observed flooding during and following Hurricane Harvey. *Journal of Exposure Science & Environmental Epidemiology*, **31** (5), 832–841. https://doi.org/10.1038/s41370-021-00361-1

87. Stearns, D. and K. Sircar, 2019: National unintentional carbon monoxide poisoning estimates using hospitalization and emergency department data. *The American Journal of Emergency Medicine*, **37** (3), 421–426. https://doi.org/10.1016/j.ajem.2018.06.002

88. Alderman, K., L.R. Turner, and S. Tong, 2012: Floods and human health: A systematic review. *Environment International*, **47**, 37–47. https://doi.org/10.1016/j.envint.2012.06.003

89. Melin, K. and N. Conte, 2018: Community pharmacists as first responders in Puerto Rico after Hurricane Maria. *Journal of the American Pharmacists Association*, **58** (2), 149. https://doi.org/10.1016/j.japh.2017.12.014

90. Azziz-Baumgartner, E., A. Wolkin, C. Sanchez, T. Bayleyegn, S. Young, S. Kieszak, K. Oberst, D. Batts, C.C. Thomas, and C. Rubin, 2005: Impact of Hurricane Ivan on pharmacies in Baldwin County Alabama. *Journal of the American Pharmacists Association*, **45** (6), 670–675. https://doi.org/10.1331/154434505774909634

91. Tarabochia-Gast, A.T., D.R. Michanowicz, and A.S. Bernstein, 2022: Flood risk to hospitals on the United States Atlantic and Gulf Coasts from hurricanes and sea level rise. *GeoHealth*, **6** (10), e2022GH000651. https://doi.org/10.1029/2022gh000651

92. Hall, T.M. and J.P. Kossin, 2019: Hurricane stalling along the North American coast and implications for rainfall. *npj Climate and Atmospheric Science*, **2** (1), 1–9. https://doi.org/10.1038/s41612-019-0074-8

93. Gori, A., N. Lin, D. Xi, and K. Emanuel, 2022: Tropical cyclone climatology change greatly exacerbates US extreme rainfall–surge hazard. *Nature Climate Change*, **12** (2), 171–178. https://doi.org/10.1038/s41558-021-01272-7

94. Zhang, G., H. Murakami, T.R. Knutson, R. Mizuta, and K. Yoshida, 2020: Tropical cyclone motion in a changing climate. *Science Advances*, **6** (17), 7610. https://doi.org/10.1126/sciadv.aaz7610

95. Balaguru, K., W. Xu, C.-C. Chang, L.R. Leung, D.R. Judi, S.M. Hagos, M.F. Wehner, J.P. Kossin, and M. Ting, 2023: Increased U.S. coastal hurricane risk under climate change. *Science Advances*, **9** (14), 0259. https://doi.org/10.1126/sciadv.adf0259

96. Garner, A.J., R.E. Kopp, and B.P. Horton, 2021: Evolving tropical cyclone tracks in the North Atlantic in a warming climate. *Earth's Future*, **9** (12), e2021EF002326. https://doi.org/10.1029/2021ef002326

97. Hotakainen, R., 2021: Ida's rapid intensification an ominous sign of climate future. *E&E News*, August 30, 2021. https://www.eenews.net/articles/idas-rapid-intensification-an-ominous-sign-of-climate-future/

98. Bhatia, K.T., G.A. Vecchi, T.R. Knutson, H. Murakami, J. Kossin, K.W. Dixon, and C.E. Whitlock, 2019: Recent increases in tropical cyclone intensification rates. *Nature Communications*, **10** (1), 635. https://doi.org/10.1038/s41467-019-08471-z

99. Balaguru, K., G.R. Foltz, L.R. Leung, W. Xu, D. Kim, H. Lopez, and R. West, 2022: Increasing hurricane intensification rate near the US Atlantic coast. *Geophysical Research Letters*, **49** (20), e2022GL099793. https://doi.org/10.1029/2022gl099793

100. Bishop, D.A., A.P. Williams, and R. Seager, 2019: Increased fall precipitation in the southeastern United States driven by higher-intensity, frontal precipitation. *Geophysical Research Letters*, **46** (14), 8300–8309. https://doi.org/10.1029/2019gl083177

101. Gershunov, A., T. Shulgina, F.M. Ralph, D.A. Lavers, and J.J. Rutz, 2017: Assessing the climate-scale variability of atmospheric rivers affecting western North America. *Geophysical Research Letters*, **44** (15), 7900–7908. https://doi.org/10.1002/2017gl074175

102. Mahoney, K., D.L. Jackson, P. Neiman, M. Hughes, L. Darby, G. Wick, A. White, E. Sukovich, and R. Cifelli, 2016: Understanding the role of atmospheric rivers in heavy precipitation in the southeast United States. *Monthly Weather Review*, **144** (4), 1617–1632. https://doi.org/10.1175/mwr-d-15-0279.1

103. Maxwell, J.T., P.A. Knapp, J.T. Ortegren, D.L. Ficklin, and P.T. Soulé, 2017: Changes in the mechanisms causing rapid drought cessation in the southeastern United States. *Geophysical Research Letters*, **44** (24), 12476–12483. https://doi.org/10.1002/2017gl076261

104. Miller, D.K., D. Hotz, J. Winton, and L. Stewart, 2018: Investigation of atmospheric rivers impacting the Pigeon River Basin of the southern Appalachian Mountains. *Weather and Forecasting*, **33** (1), 283–299. https://doi.org/10.1175/waf-d-17-0060.1

105. Miller, D.K., C.F. Miniat, R.M. Wooten, and A.P. Barros, 2019: An expanded investigation of atmospheric rivers in the southern Appalachian Mountains and their connection to landslides. *Atmosphere*, **10** (2), 71. https://doi.org/10.3390/atmos10020071

106. Mahajan, S., Q. Tang, N.D. Keen, J.-C. Golaz, and L.P. van Roekel, 2022: Simulation of ENSO teleconnections to precipitation extremes over the United States in the high-resolution version of E3SM. *Journal of Climate*, **35** (11), 3371–3393. https://doi.org/10.1175/jcli-d-20-1011.1

107. Patricola, C.M., J.P. O'Brien, M.D. Risser, A.M. Rhoades, T.A. O'Brien, P.A. Ullrich, D.A. Stone, and W.D. Collins, 2020: Maximizing ENSO as a source of western US hydroclimate predictability. *Climate Dynamics*, **54** (1), 351–372. https://doi.org/10.1007/s00382-019-05004-8

108. Alipour, A., A. Ahmadalipour, and H. Moradkhani, 2020: Assessing flash flood hazard and damages in the southeast United States. *Journal of Flood Risk Management*, **13** (2), 12605. https://doi.org/10.1111/jfr3.12605

109. Debbage, N. and J.M. Shepherd, 2019: Urban influences on the spatiotemporal characteristics of runoff and precipitation during the 2009 Atlanta flood. *Journal of Hydrometeorology*, **20** (1), 3–21. https://doi.org/10.1175/jhm-d-18-0010.1

110. Forney, R.K., N. Debbage, P. Miller, and J. Uzquiano, 2022: Urban effects on weakly forced thunderstorms observed in the Southeast United States. *Urban Climate*, **43**, 101161. https://doi.org/10.1016/j.uclim.2022.101161

111. Liu, J. and D. Niyogi, 2019: Meta-analysis of urbanization impact on rainfall modification. *Scientific Reports*, **9** (1), 7301. https://doi.org/10.1038/s41598-019-42494-2

112. McLeod, J., M. Shepherd, and C.E. Konrad, 2017: Spatio-temporal rainfall patterns around Atlanta, Georgia and possible relationships to urban land cover. *Urban Climate*, **21**, 27–42. https://doi.org/10.1016/j.uclim.2017.03.004

113. Naylor, J. and A.D. Kennedy, 2021: Variability in isolated convective activity between Louisville, Kentucky, and nearby rural locations. *Earth Interactions*, **25** (1), 33–45. https://doi.org/10.1175/ei-d-20-0012.1

114. Bhatia, K., G. Vecchi, H. Murakami, S. Underwood, and J. Kossin, 2018: Projected response of tropical cyclone intensity and intensification in a global climate model. *Journal of Climate*, **31** (20), 8281–8303. https://doi.org/10.1175/jcli-d-17-0898.1

115. Knutson, T., S.J. Camargo, J.C.L. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2019: Tropical cyclones and climate change assessment: Part I: Detection and attribution. *Bulletin of the American Meteorological Society*, **100** (10), 1987–2007. https://doi.org/10.1175/bams-d-18-0189.1

116. Knutson, T., S.J. Camargo, J.C.L. Chan, K. Emanuel, C.H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2020: Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, **101** (3), 303–322. https://doi.org/10.1175/bams-d-18-0194.1

117. Wright, D.B., T.R. Knutson, and J.A. Smith, 2015: Regional climate model projections of rainfall from U.S. landfalling tropical cyclones. *Climate Dynamics*, **45** (11), 3365–3379. https://doi.org/10.1007/s00382-015-2544-y

118. Knutson, T.R., J.J. Sirutis, M.A. Bender, R.E. Tuleya, and B.A. Schenkel, 2022: Dynamical downscaling projections of late twenty-first-century U.S. landfalling hurricane activity. *Climatic Change*, **171** (3), 28. https://doi.org/10.1007/s10584-022-03346-7

119. Martel, J.L., F.P. Brissette, P. Lucas-Picher, M. Troin, and R. Arsenault, 2021: Climate change and rainfall intensity–duration–frequency curves: Overview of science and guidelines for adaptation. *Journal of Hydrologic Engineering*, **26** (10), 03121001. https://doi.org/10.1061/(asce)he.1943-5584.0002122

120. Cook, L.M., S. McGinnis, and C. Samaras, 2020: The effect of modeling choices on updating intensity-duration-frequency curves and stormwater infrastructure designs for climate change. *Climatic Change*, **159** (2), 289–308. https://doi.org/10.1007/s10584-019-02649-6

121. Miro, M., A.T. DeGaetano, T. Lopez-Cantu, C. Samaras, M. Webber, and K.R. Grocholski, 2021: Developing Future Projected Intensity-Duration-Frequency (IDF) Curves: A Technical Report on Data, Methods, and IDF Curves for the Chesapeake Bay Watershed and Virginia. TL-A1365-1. RAND Corporation, Santa Monica, CA, 62 pp. https://doi.org/10.7249/tla1365-1

122. Lopez-Cantu, T. and C. Samaras, 2018: Temporal and spatial evaluation of stormwater engineering standards reveals risks and priorities across the United States. *Environmental Research Letters*, **13** (7), 074006. https://doi.org/10.1088/1748-9326/aac696

123. Vu, T.M. and A.K. Mishra, 2019: Nonstationary frequency analysis of the recent extreme precipitation events in the United States. *Journal of Hydrology*, **575**, 999–1010. https://doi.org/10.1016/j.jhydrol.2019.05.090

124. Jalowska, A.M., T.L. Spero, and J.H. Bowden, 2021: Projecting changes in extreme rainfall from three tropical cyclones using the design-rainfall approach. *npj Climate and Atmospheric Science*, **4** (1), 1–8. https://doi.org/10.1038/s41612-021-00176-9

125. Bin, O. and J.B. Kruse, 2006: Real estate market response to coastal flood hazards. *Natural Hazards Review*, **7** (4), 137–144. https://doi.org/10.1061/(asce)1527-6988(2006)7:4(137)

126. Wang, Z., S. Zlatanova, and P. van Oosterom, 2017: Path planning for first responders in the presence of moving obstacles with uncertain boundaries. *IEEE Transactions on Intelligent Transportation Systems*, **18** (8), 2163–2173. https://doi.org/10.1109/tits.2016.2634079

127. Gori, A., R. Blessing, A. Juan, S. Brody, and P. Bedient, 2019: Characterizing urbanization impacts on floodplain through integrated land use, hydrologic, and hydraulic modeling. *Journal of Hydrology*, **568**, 82–95. https://doi.org/10.1016/j.jhydrol.2018.10.053

128. Ghanbari, M., M. Arabi, S. Kao, J. Obeysekera, and W. Sweet, 2021: Climate change and changes in compound coastal-riverine flooding hazard along the U.S. coasts. *Earth's Future*, **9** (5), e2021EF002055. https://doi.org/10.1029/2021ef002055

129. Fiaschi, S. and S. Wdowinski, 2020: Local land subsidence in Miami Beach (FL) and Norfolk (VA) and its contribution to flooding hazard in coastal communities along the U.S. Atlantic coast. *Ocean & Coastal Management*, **187**, 105078. https://doi.org/10.1016/j.ocecoaman.2019.105078

130. Smart, L.S., P.J. Taillie, B. Poulter, J. Vukomanovic, K.K. Singh, J.J. Swenson, H. Mitasova, J.W. Smith, and R.K. Meentemeyer, 2020: Aboveground carbon loss associated with the spread of ghost forests as sea levels rise. *Environmental Research Letters*, **15** (10), 104028. https://doi.org/10.1088/1748-9326/aba136

131. Tully, K., K. Gedan, R. Epanchin-Niell, A. Strong, E.S. Bernhardt, T. BenDor, M. Mitchell, J. Kominoski, T.E. Jordan, S.C. Neubauer, and N.B. Weston, 2019: The invisible flood: The chemistry, ecology, and social implications of coastal saltwater intrusion. *BioScience*, **69** (5), 368–378. https://doi.org/10.1093/biosci/biz027

132. Gibson, N., S. McNulty, C. Miller, M. Gavazzi, E. Worley, D. Keesee, and D. Hollinger, 2021: Identification, Mitigation, and Adaptation to Salinization on Working Lands in the U.S. Southeast. Gen. Tech. Rep. SRS-259. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 69 pp. https://doi.org/10.2737/srs-gtr-259

133. CO-OPS, 2023: Annual High Tide Flooding Outlook. National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services, accessed August 15, 2023. https://tidesandcurrents.noaa.gov/high-tide-flooding/annual-outlook.html

134. Findling, M.T.G., R.J. Blendon, J.M. Benson, and C. Miller, 2022: The unseen picture: Issues with health care, discrimination, police and safety, and housing experienced by Native American populations in rural America. *The Journal of Rural Health*, **38** (1), 180–186. https://doi.org/10.1111/jrh.12517

135. Ching, A., L. Morrison, and M. Kelley, 2020: Living with natural hazards: Tropical storms, lava flows and the resilience of island residents. *International Journal of Disaster Risk Reduction*, **47**, 101546. https://doi.org/10.1016/j.ijdrr.2020.101546

136. Farrell, J., P.B. Burow, K. McConnell, J. Bayham, K. Whyte, and G. Koss, 2021: Effects of land dispossession and forced migration on Indigenous peoples in North America. *Science*, **374** (6567), 4943. https://doi.org/10.1126/science.abe4943

137. King, D.N., J. Goff, and A. Skipper, 2007: Māori environmental knowledge and natural hazards in Aotearoa-New Zealand. *Journal of the Royal Society of New Zealand*, **37** (2), 59–73. https://doi.org/10.1080/03014220709510536

138. Oliver-Smith, A., 2009: *Sea Level Rise and the Vulnerability of Coastal Peoples: Responding to the Local Challenges of Global Climate Change in the 21st Century*. *InterSecTions: 'Interdisciplinary Security ConnecTions'*. United Nations University, Institute for Environment and Human Security, Bonn, Germany. https://www.unisdr.org/files/14028_4097.pdf

139. Burnette, C.E., 2018: Family and cultural protective factors as the bedrock of resilience and growth for Indigenous women who have experienced violence. *Journal of Family Social Work*, **21** (1), 45–62. https://doi.org/10.1080/10522158.2017.1402532

140. Weiskopf, S.R., M.A. Rubenstein, L.G. Crozier, S. Gaichas, R. Griffis, J.E. Halofsky, K.J. Hyde, T.L. Morelli, J.T. Morisette, R.C. Muñoz, A.J. Pershing, D.L. Petersone, R. Poudel, M.D. Staudinger, A.E. Sutton-Grier, L. Thompson, J. Vose, J.F. Weltzin, and K.P. Whyte, 2020: Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, **733**, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782

141. Whitney, C.K., A. Frid, B.K. Edgar, J. Walkus, P. Siwallace, I.L. Siwallace, and N.C. Ban, 2020: "Like the plains people losing the buffalo": Perceptions of climate change impacts, fisheries management, and adaptation actions by Indigenous peoples in coastal British Columbia, Canada. *Ecology and Society*, **25** (4), 33. https://doi.org/10.5751/es-12027-250433

142. Rogers, L.A., R. Griffin, T. Young, E. Fuller, K.S. Martin, and M.L. Pinsky, 2019: Shifting habitats expose fishing communities to risk under climate change. *Nature Climate Change*, **9** (7), 512–516. https://doi.org/10.1038/s41558-019-0503-z

143. Pearson, J., G. Jackson, and K.E. McNamara, 2023: Climate-driven losses to Indigenous and local knowledge and cultural heritage. *The Anthropocene Review*, **10** (2), 343–366. https://doi.org/10.1177/20530196211005482

144. Anderson, D.G., T.G. Bissett, S.J. Yerka, J.J. Wells, E.C. Kansa, S.W. Kansa, K.N. Myers, R.C. DeMuth, and D.A. White, 2017: Sea-level rise and archaeological site destruction: An example from the southeastern United States using DINAA (Digital Index of North American Archaeology). *PLoS ONE*, **12** (11), e0188142. https://doi.org/10.1371/journal.pone.0188142

145. Osland, M.J., B. Chivoiu, N.M. Enwright, K.M. Thorne, G.R. Guntenspergen, J.B. Grace, L.L. Dale, W. Brooks, N. Herold, J.W. Day, F.H. Sklar, and C.M. Swarzenzki, 2022: Migration and transformation of coastal wetlands in response to rising seas. *Science Advances*, **8** (26), 5174. https://doi.org/10.1126/sciadv.abo5174

146. Aune, K.T., D. Gesch, and G.S. Smith, 2020: A spatial analysis of climate gentrification in Orleans Parish, Louisiana post-Hurricane Katrina. *Environmental Research*, **185**, 109384. https://doi.org/10.1016/j.envres.2020.109384

147. Bonjour, R., 2019: Flooding the cities: How land use policies contribute to climate gentrification. *Seton Hall Legislative Journal*, **44** (1), 91–114. https://scholarship.shu.edu/shlj/vol44/iss1/4

148. Marandi, A. and K.L. Main, 2021: Vulnerable city, recipient city, or climate destination? Towards a typology of domestic climate migration impacts in US cities. *Journal of Environmental Studies and Sciences*, **11** (3), 465–480. https://doi.org/10.1007/s13412-021-00712-2

149. Evans, L.E., N. Dolšak, M.T. Plog, and A. Prakash, 2020: Native American tribal governments, cross-sectoral climate policy, and the role of intertribal networks. *Climatic Change*, **160** (1), 35–43. https://doi.org/10.1007/s10584-019-02641-0

150. Constible, J., 2022: Hazard planners aren't planning for heat hazards. *Natural Resources Defense Council Blog*. https://www.nrdc.org/bio/juanita-constible/hazard-planners-arent-planning-heat-hazards

151. Horney, J., M. Nguyen, D. Salvesen, C. Dwyer, J. Cooper, and P. Berke, 2017: Assessing the quality of rural hazard mitigation plans in the southeastern United States. *Journal of Planning Education and Research*, **37** (1), 56–65. https://doi.org/10.1177/0739456x16628605

152. Moore, M., P. Chaney, E. Brantley, and C. Burton, 2021: Drought management plans of major cities in Alabama v. California. *Southeastern Geographer*, **61**, 31–48. https://doi.org/10.1353/sgo.2021.0003

153. Moore, M.K. 2019: Drought Management Plans in Major Cities of the Southeastern U.S. v. Western U.S. Master of Science, Auburn University. https://etd.auburn.edu//handle/10415/6686

154. Mach, K.J. and A.R. Siders, 2021: Reframing strategic, managed retreat for transformative climate adaptation. *Science*, **372** (6548), 1294–1299. https://doi.org/10.1126/science.abh1894

155. Weber, A., 2021: Building resilience, BRIC by BRIC. Natural Resources Defense Council. https://www.nrdc.org/experts/anna-weber/building-resilience-bric-bric

156. FEMA, 2021: 2022–2026 FEMA Strategic Plan: Building the FEMA Our Nation Needs and Deserves. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/about/strategic-plan

157. FEMA, 2021: FEMA Resources for Climate Resilience. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_resources-climate-resilience.pdf

158. IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp. https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/

159. Meerow, S. and S.C. Woodruff, 2020: Seven principles of strong climate change planning. *Journal of the American Planning Association*, **86** (1), 39–46. https://doi.org/10.1080/01944363.2019.1652108

160. Woodruff, S., A.O. Bowman, B. Hannibal, G. Sansom, and K. Portney, 2021: Urban resilience: Analyzing the policies of U.S. cities. *Cities*, **115**, 103239. https://doi.org/10.1016/j.cities.2021.103239

161. Woodruff, S., S. Meerow, P. Gilbertson, B. Hannibal, M. Matos, M. Roy, M. Malecha, S. Yu, and P. Berke, 2021: Is flood resilience planning improving? A longitudinal analysis of networks of plans in Boston and Fort Lauderdale. *Climate Risk Management*, **34**, 100354. https://doi.org/10.1016/j.crm.2021.100354

162. Freudenberg, R., E. Calvin, L. Tolkoff, and D. Brawley, 2016: Buy-In for Buyouts: The Case for Managed Retreat from Flood Zones. Lincoln Institute of Land and Policy, Cambridge, MA. https://www.lincolninst.edu/sites/default/files/pubfiles/buy-in-for-buyouts-full.pdf

163. Godschalk, D.R., A. Rose, E. Mittler, K. Porter, and C.T. West, 2009: Estimating the value of foresight: Aggregate analysis of natural hazard mitigation benefits and costs. *Journal of Environmental Planning and Management*, **52** (6), 739–756. https://doi.org/10.1080/09640560903083715

164. Mach, K.J., C.M. Kraan, M. Hino, A.R. Siders, E.M. Johnston, and C.B. Field, 2019: Managed retreat through voluntary buyouts of flood-prone properties. *Science Advances*, **5** (10), 8995. https://doi.org/10.1126/sciadv.aax8995

165. Berke, P.R., W. Lyles, and G. Smith, 2014: Impacts of federal and state hazard mitigation policies on local land use policy. *Journal of Planning Education and Research*, **34** (1), 60–76. https://doi.org/10.1177/0739456x13517004

166. Burby, R.J., 2006: Hurricane Katrina and the paradoxes of government disaster policy: Bringing about wise governmental decisions for hazardous areas. *The ANNALS of the American Academy of Political and Social Science*, **604** (1), 171–191. https://doi.org/10.1177/0002716205284676

167. Butler, W.H., R.E. Deyle, and C. Mutnansky, 2016: Low-regrets incrementalism: Land use planning adaptation to accelerating sea level rise in Florida's coastal communities. *Journal of Planning Education and Research*, **36** (3), 319–332. https://doi.org/10.1177/0739456x16647161

168. Smith, G., J. Whitehead, N. Kaza, J. Park, J. Pine, R. Kolar, D. Sandler, and E. Thomas, 2013: Aggregate Flood Hazard Risk Reduction Scoping Project. U.S. Department of Homeland Security, Coastal Resilience Center. http://coastalhazardscenter.org/dev/wp-content/uploads/2013/12/Final_GS_12_16_13.pdf

169. Young, A.W., 2018: How to retreat: The necessary transition from buyouts to leasing. *Coastal Management*, **46** (5), 527–535. https://doi.org/10.1080/08920753.2018.1498716

170. McGhee, D.J., S.B. Binder, and E.A. Albright, 2020: First, do no harm: Evaluating the vulnerability reduction of post-disaster home buyout programs. *Natural Hazards Review*, **21** (1), 05019002. https://doi.org/10.1061/(asce)nh.1527-6996.0000337

171. Zavar, E. and L.A. Fischer, 2021: Fractured landscapes: The racialization of home buyout programs and climate adaptation. *Current Research in Environmental Sustainability*, **3**, 100043. https://doi.org/10.1016/j.crsust.2021.100043

172. Clark, M.B., E. Nkonya, and G.L. Galford, 2022: Flocking to fire: How climate and natural hazards shape human migration across the United States. *Frontiers in Human Dynamics*, **4**, 886545. https://doi.org/10.3389/fhumd.2022.886545

173. Smith, G.P. and M.T. Nguyen, 2021: University-public partnerships for disaster recovery: Promoting community resilience through research, teaching, and engagement. *Journal of Community Engagement and Scholarship*, **14** (1), 4. https://jces.ua.edu/articles/10.54656/NPFV8067

174. Baker, C.K., S.B. Binder, A. Greer, P. Weir, and K. Gates, 2018: Integrating community concerns and recommendations into home buyout and relocation policy. *Risk, Hazards & Crisis in Public Policy*, **9** (4), 455–479. https://doi.org/10.1002/rhc3.12144

175. Binder, S.B. and A. Greer, 2018: Exploring the Role of Implementing Agencies in Home Buyouts: Process, Equity, and Inclusion in Program Design and Implementation. Natural Hazards Center Quick Response Grant Report Series, 281. University of Colorado Boulder, Natural Hazards Center, Boulder, CO. https://hazards.colorado.edu/quick-response-report/exploring-the-role-of-implementing-agencies-in-home-buyouts-process-equity-and-inclusion-in-program-design-and-implementation

176. de Vries, D.H. and J.C. Fraser, 2012: Citizenship rights and voluntary decision making in post-disaster U.S. floodplain buyout mitigation programs. *International Journal of Mass Emergencies and Disasters*, **30** (1). https://hdl.handle.net/11245/1.369610

177. Elliott, J.R., P.L. Brown, and K. Loughran, 2020: Racial inequities in the federal buyout of flood-prone homes: A nationwide assessment of environmental adaptation. *Socius*, **6**, 2378023120905439. https://doi.org/10.1177/2378023120905439

178. Fraser, J., R. Elmore, D. Godschalk, and W. Rohe, 2003: Implementing Floodplain Land Acquisition Programs in Urban Localities. University of North Carolina at Chapel Hill, Center for Urban & Regional Studies, Chapel Hill, NC. https://www.academia.edu/27892388/implementing_floodplain_land_acquisition_programs_in_urban_localities

179. Nguyen, C.N., 2020: Homeowners' choice when the government proposes a managed retreat. *International Journal of Disaster Risk Reduction*, **47**, 101543. https://doi.org/10.1016/j.ijdrr.2020.101543

180. Flink, C.A., 2020: *The Greenway Imperative: Connecting Communities and Landscapes for a Sustainable Future*. University of Florida Press, 344 pp. https://upf.com/book.asp?id=9781683401155#

181. Highfield, W., A. Kayode, S. Brody, C. Shepard, and L. Verdone, 2019: Strategic Property Buyouts to Enhance Flood Resilience: Creating a Model for Flood Risk Reduction, Community Protection and Environmental Gains. The Nature Conservancy, Washington, DC. https://www.nature.org/content/dam/tnc/nature/en/documents/harveybuyoutsummary.pdf

182. Kihslinger, R., A. Streitwieser, M. Lerner, N. Moraga-Lewy, K. James-Kavanaugh, D. Salvesen, J. Anagnost, T. Chandler, C. Foster, and S. Liu, 2017: Floodplain Buyouts: An Action Guide for Local Governments on How to Maximize Community Benefits, Habitat Connectivity, and Resilience. Environmental Law Institute and University of North Carolina at Chapel Hill, Washington, DC and Chapel Hill, NC. https://www.eli.org/sites/default/files/eli-pubs/actionguide-web.pdf

183. Keenan, J.M., T. Hill, and A. Gumber, 2018: Climate gentrification: From theory to empiricism in Miami-Dade County, Florida. *Environmental Research Letters*, **13** (5), 054001. https://doi.org/10.1088/1748-9326/aabb32

184. Taylor, Z.J. and M.B. Aalbers, 2022: Climate gentrification: Risk, rent, and restructuring in Greater Miami. *Annals of the American Association of Geographers*, **112** (6), 1685–1701. https://doi.org/10.1080/24694452.2021.2000358

185. Treuer, G., K. Broad, and R. Meyer, 2018: Using simulations to forecast homeowner response to sea level rise in South Florida: Will they stay or will they go? *Global Environmental Change*, **48**, 108–118. https://doi.org/10.1016/j.gloenvcha.2017.10.008

186. Anguelovski, I., J.J.T. Connolly, H. Cole, M. Garcia-Lamarca, M. Triguero-Mas, F. Baró, N. Martin, D. Conesa, G. Shokry, C.P. del Pulgar, L.A. Ramos, A. Matheney, E. Gallez, E. Oscilowicz, J.L. Máñez, B. Sarzo, M.A. Beltrán, and J.M. Minaya, 2022: Green gentrification in European and North American cities. *Nature Communications*, **13** (1), 3816. https://doi.org/10.1038/s41467-022-31572-1

187. Melix, B.L., A. Jackson, W. Butler, T. Holmes, and C.K. Uejio, 2022: Locating neighborhood displacement risks to climate gentrification pressures in three coastal counties in Florida. *The Professional Geographer*, **75** (1), 31–43. https://doi.org/10.1080/00330124.2022.2087695

188. Gardiner, E.P., D.D. Herring, and J.F. Fox, 2019: The U.S. Climate Resilience Toolkit: Evidence of progress. *Climatic Change*, **153** (4), 477–490. https://doi.org/10.1007/s10584-018-2216-0

189. Resilient Cities Network, 2022: Resilient Cities Network [Website]. https://resilientcitiesnetwork.org/

190. APHA, 2021: Climate Change and Health Playbook: Adaptation Planning for Justice, Equity, Diversity and Inclusion. American Public Health Association. https://apha.org/topics-and-issues/climate-change/jedi

191. Grace-McCaskey, C.A., S.C. Pearce, L. Harris, M. Corra, and K.J. Evans, 2021: Finding voices in the floods of Freedom Hill: Innovating solutions in Princeville, North Carolina. *Journal of Environmental Studies and Sciences*, **11** (3), 341–351. https://doi.org/10.1007/s13412-021-00701-5

192. Blue, V.E., 2000: Reclaiming sacred ground: How Princeville is recovering from the flood of 1999. *NC Crossroads*, **4** (3). https://www.ncpedia.org/anchor/reclaiming-sacred-ground-how

193. Jadid, R., B.M. Montoya, V. Bennett, and M.A. Gabr, 2020: Effect of repeated rise and fall of water level on seepage-induced deformation and related stability analysis of Princeville levee. *Engineering Geology*, **266**, 105458. https://doi.org/10.1016/j.enggeo.2019.105458

194. Phillips, B., P.A. Stukes, and P. Jenkins, 2012: Freedom Hill is not for sale—And neither is the Lower Ninth Ward. *Journal of Black Studies*, **43** (4), 405–426. https://doi.org/10.1177/0021934711425489

195. Ebi, K.L. and J.J. Hess, 2020: Health risks due to climate change: Inequity in causes and consequences. *Health Affairs*, **39** (12), 2056–2062. https://doi.org/10.1377/hlthaff.2020.01125

196. Dwyer-Lindgren, L., A. Bertozzi-Villa, R.W. Stubbs, C. Morozoff, J.P. Mackenbach, F.J. van Lenthe, A.H. Mokdad, and C.J.L. Murray, 2017: Inequalities in life expectancy among US counties, 1980 to 2014: Temporal trends and key drivers. *JAMA Internal Medicine*, **177** (7), 1003–1011. https://doi.org/10.1001/jamainternmed.2017.0918

197. Gong, G., S.G. Phillips, C. Hudson, D. Curti, and B.U. Philips, 2019: Higher US rural mortality rates linked to socioeconomic status, physician shortages, and lack of health insurance. *Health Affairs*, **38** (12), 2003–2010. https://doi.org/10.1377/hlthaff.2019.00722

198. Walk Score, 2022: Most Walkable Cities in the United States, Canada, and Australia on Walk Score. Redfin. https://www.walkscore.com/cities-and-neighborhoods/

199. Smart Growth America, 2021: Dangerous by Design. Smart Growth America and National Complete Streets Coalition, 38 pp. https://smartgrowthamerica.org/resources/dangerous-by-design-2021-report/

200. NHTSA, n.d.: Fatality Analysis Reporting System. U.S. Department of Transportation, National Highway Traffic Safety Administration, accessed November 28, 2022. https://www.nhtsa.gov/crash-data-systems/fatality-analysis-reporting-system

201. Meyer, P.A., P.W. Yoon, and R.B. Kaufmann, 2013: Introduction: CDC Health Disparities and Inequalities Report—United States, 2013. *Morbidity and Mortality Weekly Report*, **62** (3), 3–5. http://www.cdc.gov/mmwr/pdf/other/su6203.pdf

202. Yearby, R., 2018: Racial disparities in health status and access to healthcare: The continuation of inequality in the United States due to structural racism. *The American Journal of Economics and Sociology*, **77** (3–4), 1113–1152. https://doi.org/10.1111/ajes.12230

203. Savitz, D.A. and H. Hu, 2021: Ambient heat and stillbirth in northern and central Florida. *Environmental Research*, **199**, 111262. https://doi.org/10.1016/j.envres.2021.111262

204. Son, J.-Y., H.M. Choi, M.L. Miranda, and M.L. Bell, 2022: Exposure to heat during pregnancy and preterm birth in North Carolina: Main effect and disparities by residential greenness, urbanicity, and socioeconomic status. *Environmental Research*, **204**, 112315. https://doi.org/10.1016/j.envres.2021.112315

205. Syed, S., T.L. O'Sullivan, and K.P. Phillips, 2022: Extreme heat and pregnancy outcomes: A scoping review of the epidemiological evidence. *International Journal of Environmental Research and Public Health*, **19** (4), 2412. https://doi.org/10.3390/ijerph19042412

206. Cheng, J., Z. Xu, H. Bambrick, V. Prescott, N. Wang, Y. Zhang, H. Su, S. Tong, and W. Hu, 2019: Cardiorespiratory effects of heatwaves: A systematic review and meta-analysis of global epidemiological evidence. *Environmental Research*, **177**, 108610. https://doi.org/10.1016/j.envres.2019.108610

207. Uejio, C.K., A.P. Joiner, E. Gonsoroski, J.D. Tamerius, J. Jung, T.P. Moran, and A.H. Yancey, 2022: The association of indoor heat exposure with diabetes and respiratory 9-1-1 calls through emergency medical dispatch and services documentation. *Environmental Research*, **212**, 113271. https://doi.org/10.1016/j.envres.2022.113271

208. Sheffield, P.E., M.T. Herrera, E.J. Kinnee, and J.E. Clougherty, 2018: Not so little differences: Variation in hot weather risk to young children in New York City. *Public Health*, **161**, 119–126. https://doi.org/10.1016/j.puhe.2018.06.004

209. Ebi, K.L., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, and O. Jay, 2021: Hot weather and heat extremes: Health risks. *The Lancet*, **398** (10301), 698–708. https://doi.org/10.1016/s0140-6736(21)01208-3

210. Nori-Sarma, A., S. Sun, Y. Sun, K.R. Spangler, R. Oblath, S. Galea, J.L. Gradus, and G.A. Wellenius, 2022: Association between ambient heat and risk of emergency department visits for mental health among US adults, 2010 to 2019. *JAMA Psychiatry*, **79** (4), 341–349. https://doi.org/10.1001/jamapsychiatry.2021.4369

211. Thompson, R., R. Hornigold, L. Page, and T. Waite, 2018: Associations between high ambient temperatures and heat waves with mental health outcomes: A systematic review. *Public Health*, **161**, 171–191. https://doi.org/10.1016/j.puhe.2018.06.008

212. Atlantic Council, 2021: Extreme Heat: The Economic and Social Consequences for the United States. Atlantic Council's Adrienne Arsht Rockefeller Foundation Resilience Center, Washington, DC. https://www.atlanticcouncil.org/wp-content/uploads/2021/08/Extreme-Heat-Report-2021.pdf

213. Dahl, K. and R. Licker, 2021: Too Hot to Work: Assessing the Threats Climate Change Poses to Outdoor Workers. Union of Concerned Scientists, Cambridge, MA. https://doi.org/10.47923/2021.14236

214. Adams, W.M., 2019: Exertional heat stroke within secondary school athletics. *Current Sports Medicine Reports*, **18** (4), 149–153. https://doi.org/10.1249/jsr.0000000000000585

215. Cooper, E.R., M.S. Ferrara, D.J. Casa, J.W. Powell, S.P. Broglio, J.E. Resch, and R.W. Courson, 2016: Exertional heat illness in American football players: When is the risk greatest? *Journal of Athletic Training*, **51** (8), 593–600. https://doi.org/10.4085/1062-6050-51.8.08

216. Yeargin, S.W., T.P. Dompier, D.J. Casa, R.M. Hirschhorn, and Z.Y. Kerr, 2019: Epidemiology of exertional heat illnesses in National Collegiate Athletic Association athletes during the 2009–2010 through 2014–2015 academic years. *Journal of Athletic Training*, **54** (1), 55–63. https://doi.org/10.4085/1062-6050-504-17

217. Holt, D., 2015: Heat in US Prisons and Jails: Corrections and the Challenge of Climate Change. Columbia Law School, Sabin Center for Climate Change Law, New York, NY, 144 pp. https://nicic.gov/heat-us-prisons-and-jails-corrections-and-challenge-climate-change

218. Schwarz, L., E.M. Castillo, T.C. Chan, J.J. Brennan, E.S. Sbiroli, G. Carrasco-Escobar, A. Nguyen, R.E.S. Clemesha, A. Gershunov, and T. Benmarhnia, 2022: Heat waves and emergency department visits among the homeless, San Diego, 2012–2019. *American Journal of Public Health*, **112** (1), 98–106. https://doi.org/10.2105/ajph.2021.306557

219. Obringer, R., R. Nateghi, D. Maia-Silva, S. Mukherjee, V. Cr, D.B. McRoberts, and R. Kumar, 2022: Implications of increasing household air conditioning use across the United States under a warming climate. *Earth's Future*, **10** (1), e2021EF002434. https://doi.org/10.1029/2021ef002434

220. Romitti, Y., I. Sue Wing, K.R. Spangler, and G.A. Wellenius, 2022: Inequality in the availability of residential air conditioning across 115 US metropolitan areas. *PNAS Nexus*, **1** (4), 210. https://doi.org/10.1093/pnasnexus/pgac210

221. EIA. 2020: Forms EIA-457A and EIA-457C of the 2015 Residential Energy Consumption Survey. U.S. Energy Information Administration, Office of Energy Demand and Integrated Statistics. https://www.eia.gov/consumption/residential/data/2020/hc/pdf/hc%2011.1.pdf

222. Bryan, W. and M. Kelley, 2021: Energy Insecurity Fundamentals for the Southeast. Southeast Energy Efficiency Alliance, 19 pp. https://issuu.com/seealliance/docs/report_energyinsecurity_02_15_2021_v1

223. Stone Jr., B., E. Mallen, M. Rajput, A. Broadbent, E.S. Krayenhoff, G. Augenbroe, and M. Georgescu, 2021: Climate change and infrastructure risk: Indoor heat exposure during a concurrent heat wave and blackout event in Phoenix, Arizona. *Urban Climate*, **36**, 100787. https://doi.org/10.1016/j.uclim.2021.100787

224. Stone Jr., B., E. Mallen, M. Rajput, C.J. Gronlund, A.M. Broadbent, E.S. Krayenhoff, G. Augenbroe, M.S. O'Neill, and M. Georgescu, 2021: Compound climate and infrastructure events: How electrical grid failure alters heat wave risk. *Environmental Science & Technology*, **55** (10), 6957–6964. https://doi.org/10.1021/acs.est.1c00024

225. van Vliet, M.T.H., J.R. Yearsley, F. Ludwig, S. Vögele, D.P. Lettenmaier, and P. Kabat, 2012: Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, **2** (9), 676–681. https://doi.org/10.1038/nclimate1546

226. Mallen, E., 2022: U.S. Blackout Tracker. Urban Climate Lab, accessed November 18, 2022. https://urbanclimate.gatech.edu/current-projects/blackout-tracker/

227. Bryan, W.D., 2020: Energy Insecurity in the Southeast [Story Map]. Southeast Energy Efficiency Alliance, accessed August 16, 2023. https://storymaps.arcgis.com/stories/ce22fa68b37141f388d8df06c9bd4fb1

228. Allen, M., J. Hoffman, J.L. Whytlaw, and N. Hutton, 2022: Assessing Virginia cooling centers as a heat mitigation strategy. *Journal of Emergency Management*, **20** (3), 205–224. https://doi.org/10.5055/jem.0671

229. Tomer, A. and R. Puentes, 2011: Transit Access and Zero-Vehicle Households. The Brookings Institution. https://www.brookings.edu/research/transit-access-and-zero-vehicle-households/

230. Coffel, E.D., R.M. Horton, and A. Sherbinin, 2018: Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century. *Environmental Research Letters*, **13** (1), 014001. https://doi.org/10.1088/1748-9326/aaa00e

231. EPA, 2021: Climate Change Indicators: Heat Waves. U.S. Environmental Protection Agency. https://www.epa.gov/climate-indicators/climate-change-indicators-heat-waves

232. Heo, S., M.L. Bell, and J.-T. Lee, 2019: Comparison of health risks by heat wave definition: Applicability of wet-bulb globe temperature for heat wave criteria. *Environmental Research*, **168**, 158–170. https://doi.org/10.1016/j.envres.2018.09.032

233. Rennie, J.J., M.A. Palecki, S.P. Heuser, and H.J. Diamond, 2021: Developing and validating heat exposure products using the U.S. Climate Reference Network. *Journal of Applied Meteorology and Climatology*, **60** (4), 543–558. https://doi.org/10.1175/jamc-d-20-0282.1

234. Knutson, T.R. and J.J. Ploshay, 2016: Detection of anthropogenic influence on a summertime heat stress index. *Climatic Change*, **138** (1), 25–39. https://doi.org/10.1007/s10584-016-1708-z

235. Li, C., X. Zhang, F. Zwiers, Y. Fang, and A.M. Michalak, 2017: Recent very hot summers in northern hemispheric land areas measured by wet bulb globe temperature will be the norm within 20 years. *Earth's Future*, **5** (12), 1203–1216. https://doi.org/10.1002/2017ef000639

236. Oke, T.R., 1982: The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, **108** (455), 1–24. https://doi.org/10.1002/qj.49710845502

237. Shandas, V., J. Voelkel, J. Williams, and J. Hoffman, 2019: Integrating satellite and ground measurements for predicting locations of extreme urban heat. *Climate*, **7** (1), 5. https://doi.org/10.3390/cli7010005

238. Benz, S.A. and J.A. Burney, 2021: Widespread race and class disparities in surface urban heat extremes across the United States. *Earth's Future*, **9** (7), e2021EF002016. https://doi.org/10.1029/2021ef002016

239. Shire, J., A. Vaidyanathan, M. Lackovic, and T. Bunn, 2020: Association between work-related hyperthermia emergency department visits and ambient heat in five southeastern states, 2010–2012—A case-crossover study. *GeoHealth*, **4** (8), 2019GH000241. https://doi.org/10.1029/2019gh000241

240. Lancet Countdown, 2020: Compounding Crises of Our Time During Hurricane Laura. 2020 Case Study 1. Lancet Countdown. https://www.lancetcountdownus.org/2020-case-study-1/

241. Baublitz, C.B., A.M. Fiore, O.E. Clifton, J. Mao, J. Li, G. Correa, D.M. Westervelt, L.W. Horowitz, F. Paulot, and A.P. Williams, 2020: Sensitivity of tropospheric ozone over the Southeast USA to dry deposition. *Geophysical Research Letters*, **47** (7), 2020GL087158. https://doi.org/10.1029/2020gl087158

242. Fu, T.M. and H. Tian, 2019: Climate change penalty to ozone air quality: Review of current understandings and knowledge gaps. *Current Pollution Reports*, **5** (3), 159–171. https://doi.org/10.1007/s40726-019-00115-6

243. Zhang, Y. and Y. Wang, 2016: Climate-driven ground-level ozone extreme in the fall over the southeast United States. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (36), 10025–10030. https://doi.org/10.1073/pnas.1602563113

244. Brey, S.J., E.A. Barnes, J.R. Pierce, C. Wiedinmyer, and E.V. Fischer, 2018: Environmental conditions, ignition type, and air quality impacts of wildfires in the southeastern and western United States. *Earth's Future*, **6** (10), 1442–1456. https://doi.org/10.1029/2018ef000972

245. Guan, S., D.C. Wong, Y. Gao, T. Zhang, and G. Pouliot, 2020: Impact of wildfire on particulate matter in the southeastern United States in November 2016. *Science of The Total Environment*, **724**, 138354. https://doi.org/10.1016/j.scitotenv.2020.138354

246. Jaffe, D.A., S.M. O'Neill, N.K. Larkin, A.L. Holder, D.L. Peterson, J.E. Halofsky, and A.G. Rappold, 2020: Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air & Waste Management Association*, **70** (6), 583–615. https://doi.org/10.1080/10962247.2020.1749731

247. van Donkelaar, A., R.V. Martin, C. Li, and R.T. Burnett, 2019: Regional estimates of chemical composition of fine particulate matter using a combined geoscience-statistical method with information from satellites, models, and monitors. *Environmental Science & Technology*, **53** (5), 2595–2611. https://doi.org/10.1021/acs.est.8b06392

248. Pye, H.O.T., C.K. Ward-Caviness, B.N. Murphy, K.W. Appel, and K.M. Seltzer, 2021: Secondary organic aerosol association with cardiorespiratory disease mortality in the United States. *Nature Communications*, **12** (1), 7215. https://doi.org/10.1038/s41467-021-27484-1

249. Boing, A.F., P. deSouza, A.C. Boing, R. Kim, and S.V. Subramanian, 2022: Air pollution, socioeconomic status, and age-specific mortality risk in the United States. *JAMA Network Open*, **5** (5), e2213540. https://doi.org/10.1001/jamanetworkopen.2022.13540

250. Colmer, J., I. Hardman, J. Shimshack, and J. Voorheis, 2020: Disparities in $PM_{2.5}$ air pollution in the United States. *Science*, **369** (6503), 575–578. https://doi.org/10.1126/science.aaz9353

251. Fann, N.L., C.G. Nolte, M.C. Sarofim, J. Martinich, and N.J. Nassikas, 2021: Associations between simulated future changes in climate, air quality, and human health. *JAMA Network Open*, **4** (1), e2032064. https://doi.org/10.1001/jamanetworkopen.2020.32064

252. Saari, R.K., Y. Mei, E. Monier, and F. Garcia-Menendez, 2019: Effect of health-related uncertainty and natural variability on health impacts and cobenefits of climate policy. *Environmental Science & Technology*, **53** (3), 1098–1108. https://doi.org/10.1021/acs.est.8b05094

253. Anderegg, W.R.L., J.T. Abatzoglou, L.D.L. Anderegg, L. Bielory, P.L. Kinney, and L. Ziska, 2021: Anthropogenic climate change is worsening North American pollen seasons. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (7), e2013284118. https://doi.org/10.1073/pnas.2013284118

254. Manangan, A., C. Brown, S. Saha, J. Bell, J. Hess, C. Uejio, S. Fineman, and P. Schramm, 2021: Long-term pollen trends and associations between pollen phenology and seasonal climate in Atlanta, Georgia (1992–2018). *Annals of Allergy, Asthma & Immunology*, **127** (4), 471–480. https://doi.org/10.1016/j.anai.2021.07.012

255. Radeloff, V.C., D.P. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar-Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, and S.I. Stewart, 2018: Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (13), 3314–3319. https://doi.org/10.1073/pnas.1718850115

256. Gao, P., A.J. Terando, J.A. Kupfer, J. Morgan Varner, M.C. Stambaugh, T.L. Lei, and J. Kevin Hiers, 2021: Robust projections of future fire probability for the conterminous United States. *Science of The Total Environment*, **789**, 147872. https://doi.org/10.1016/j.scitotenv.2021.147872

257. Andersen, L.M. and M.M. Sugg, 2019: Geographic multi-criteria evaluation and validation: A case study of wildfire vulnerability in western North Carolina, USA following the 2016 wildfires. *International Journal of Disaster Risk Reduction*, **39**, 101123. https://doi.org/10.1016/j.ijdrr.2019.101123

258. James, N.A., K.L. Abt, G.E. Frey, X. Han, and J.P. Prestemon, 2020: Fire in the Southern Appalachians: Understanding Impacts, Interventions, and Future Fire Events. e-Gen. Tech. Rep. SRS-249. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 34 pp. https://doi.org/10.2737/srs-gtr-249

259. Haikerwal, A., F. Reisen, M.R. Sim, M.J. Abramson, C.P. Meyer, F.H. Johnston, and M. Dennekamp, 2015: Impact of smoke from prescribed burning: Is it a public health concern? *Journal of the Air & Waste Management Association*, **65** (5), 592–598. https://doi.org/10.1080/10962247.2015.1032445

260. Afrin, S. and F. Garcia-Menendez, 2021: Potential impacts of prescribed fire smoke on public health and socially vulnerable populations in a southeastern U.S. state. *Science of The Total Environment*, **794**, 148712. https://doi.org/10.1016/j.scitotenv.2021.148712

261. Afrin, S. and F. Garcia-Menendez, 2020: The influence of prescribed fire on fine particulate matter pollution in the southeastern United States. *Geophysical Research Letters*, **47** (15), e2020GL088988. https://doi.org/10.1029/2020gl088988

262. Kupfer, J.A., A.J. Terando, P. Gao, C. Teske, and J.K. Hiers, 2020: Climate change projected to reduce prescribed burning opportunities in the south-eastern United States. *International Journal of Wildland Fire*, **29** (9), 764–778. https://doi.org/10.1071/wf19198

263. Park Williams, A., B.I. Cook, J.E. Smerdon, D.A. Bishop, R. Seager, and J.S. Mankin, 2017: The 2016 southeastern U.S. drought: An extreme departure from centennial wetting and cooling. *Journal of Geophysical Research: Atmospheres*, **122** (20), 10888–10905. https://doi.org/10.1002/2017jd027523

264. Gabbert, B., 2016: Analyzing the fire that burned into Gatlinburg. *Wildfire Today*, December 5, 2016. https://wildfiretoday.com/2016/12/05/analyzing-the-fire-that-burned-into-gatlinburg/

265. Gaines, J., 2018: Gatlinburg wildfire, two-year mark: Safety changes made, rebuilding continues. *Knox News*, November 27, 2018. https://www.knoxnews.com/story/news/2018/11/28/gatlinburg-wildfire-sevier-county-smoky-mountains-two-years-later/2029279002/

266. Dai, Y., S. Yang, D. Zhao, C. Hu, W. Xu, D.M. Anderson, Y. Li, X.-P. Song, D.G. Boyce, L. Gibson, C. Zheng, and L. Feng, 2023: Coastal phytoplankton blooms expand and intensify in the 21st century. *Nature*, **615** (7951), 280–284. https://doi.org/10.1038/s41586-023-05760-y

267. Anderson, D.M., E. Fensin, C.J. Gobler, A.E. Hoeglund, K.A. Hubbard, D.M. Kulis, J.H. Landsberg, K.A. Lefebvre, P. Provoost, M.L. Richlen, J.L. Smith, A.R. Solow, and V.L. Trainer, 2021: Marine harmful algal blooms (HABs) in the United States: History, current status and future trends. *Harmful Algae*, **102**, 101975. https://doi.org/10.1016/j.hal.2021.101975

268. Gobler, C.J., 2020: Climate change and harmful algal blooms: Insights and perspective. *Harmful Algae*, **91**, 101731. https://doi.org/10.1016/j.hal.2019.101731

269. Heil, C.A. and A.L. Muni-Morgan, 2021: Florida's harmful algal bloom (HAB) problem: Escalating risks to human, environmental and economic health with climate change. *Frontiers in Ecology and Evolution*, **9**, 646080. https://doi.org/10.3389/fevo.2021.646080

270. Bechard, A., 2020: External costs of harmful algal blooms using hedonic valuation: The impact of *Karenia brevis* on Southwest Florida. *Environmental and Sustainability Indicators*, **5**, 100019. https://doi.org/10.1016/j.indic.2020.100019

271. Bechard, A., 2020: The economic impacts of harmful algal blooms on tourism: An examination of Southwest Florida using a spline regression approach. *Natural Hazards*, **104** (1), 593–609. https://doi.org/10.1007/s11069-020-04182-7

272. Bechard, A., 2021: Gone with the wind: Declines in property values as harmful algal blooms are blown towards the shore. *The Journal of Real Estate Finance and Economics*, **62** (2), 242–257. https://doi.org/10.1007/s11146-020-09749-6

273. Vigar, M., M. Thuneibat, A. Jacobi, and V.A. Roberts, 2021: Summary Report–One Health Harmful Algal Bloom System (OHHABS), United States, 2019. U.S. Department of Health and Human Services, Atlanta, GA, 26 pp. https://stacks.cdc.gov/view/cdc/112313

274. Brown, A.R., M. Lilley, J. Shutler, C. Lowe, Y. Artioli, R. Torres, E. Berdalet, and C.R. Tyler, 2020: Assessing risks and mitigating impacts of harmful algal blooms on mariculture and marine fisheries. *Reviews in Aquaculture*, **12** (3), 1663–1688. https://doi.org/10.1111/raq.12403

275. Mishra, A., A. Alnahit, and B. Campbell, 2021: Impact of land uses, drought, flood, wildfire, and cascading events on water quality and microbial communities: A review and analysis. *Journal of Hydrology*, **596**, 125707. https://doi.org/10.1016/j.jhydrol.2020.125707

276. Parasiewicz, P., E.L. King, J.A. Webb, M. Piniewski, C. Comoglio, C. Wolter, A.D. Buijse, D. Bjerklie, P. Vezza, and A. Melcher, 2019: The role of floods and droughts on riverine ecosystems under a changing climate. *Fisheries Management and Ecology*, **26** (6), 461–473. https://doi.org/10.1111/fme.12388

277. Foss, A.J., E.J. Phlips, M. Yilmaz, and A. Chapman, 2012: Characterization of paralytic shellfish toxins from *Lyngbya wollei* dominated mats collected from two Florida springs. *Harmful Algae*, **16**, 98–107. https://doi.org/10.1016/j.hal.2012.02.004

278. Reis Costa, P., 2016: Impact and effects of paralytic shellfish poisoning toxins derived from harmful algal blooms to marine fish. *Fish and Fisheries*, **17** (1), 226–248. https://doi.org/10.1111/faf.12105

279. Alkishe, A., R.K. Raghavan, and A.T. Peterson, 2021: Likely geographic distributional shifts among medically important tick species and tick-associated diseases under climate change in North America: A review. *Insects*, **12** (3), 225. https://doi.org/10.3390/insects12030225

280. Couper, L.I., A.J. MacDonald, and E.A. Mordecai, 2021: Impact of prior and projected climate change on US Lyme disease incidence. *Global Change Biology*, **27** (4), 738–754. https://doi.org/10.1111/gcb.15435

281. Lantos, P.M., J. Tsao, M. Janko, A. Arab, M.E. Fricken, P.G. Auwaerter, L.E. Nigrovic, V. Fowler, F. Ruffin, D. Gaines, J. Broyhill, and J. Swenson, 2021: Environmental correlates of Lyme disease emergence in southwest Virginia, 2005–2014. *Journal of Medical Entomology*, **58** (4), 1680–1685. https://doi.org/10.1093/jme/tjab038

282. Seukep, S.E., K.N. Kolivras, Y. Hong, J. Li, S.P. Prisley, J.B. Campbell, D.N. Gaines, and R.L. Dymond, 2015: An examination of the demographic and environmental variables correlated with Lyme disease emergence in Virginia. *EcoHealth*, **12** (4), 634–644. https://doi.org/10.1007/s10393-015-1034-3

283. Stevens, L.K., K.N. Kolivras, Y. Hong, V.A. Thomas, J.B. Campbell, and S.P. Prisley, 2019: Future Lyme disease risk in the south-eastern United States based on projected land cover. *Geospatial Health*, **14** (1). https://doi.org/10.4081/gh.2019.751

284. Morse, W., K. Izenour, B. McKenzie, S. Lessard, and S. Zohdy, 2019: Perceptions and practices of mosquito-borne diseases in Alabama – Is concern where it should be? *BMC Public Health*, **19** (1), 987. https://doi.org/10.1186/s12889-019-7308-x

285. Kollars, T.M., 2017: Identifying health disparities of mosquito-borne diseases in low and medium income communities in Savannah, Georgia, USA. *Annals of Community Medicine and Practice*, **3** (2), 1025. https://www.jscimedcentral.com/public/assets/articles/communitymedicine-3-1024.pdf

286. Kollars, T.M., 2017: Identifying high risk areas of West Nile Virus in minority and low-income neighborhoods. *Clinical Microbiology and Infectious Diseases*, **2** (1), 1–3. https://doi.org/10.15761/cmid.1000123

287. Mental Health America, 2020: 2020 Prevalence Data. Mental Health America. https://www.nssbehavioralhealth.com/blog-nss-the-state-of-mental-health-in-america-2020-adult-prevalence-and-access-to-care/

288. Mental Health America, 2020: 2020 Access to Care Data. Mental Health America. https://www.nssbehavioralhealth.com/blog-nss-the-state-of-mental-health-in-america-2020-adult-prevalence-and-access-to-care/

289. Sugg, M., J. Runkle, R. Leeper, H. Bagli, A. Golden, L.H. Handwerger, T. Magee, C. Moreno, R. Reed-Kelly, M. Taylor, and S. Woolard, 2020: A scoping review of drought impacts on health and society in North America. *Climatic Change*, **162** (3), 1177–1195. https://doi.org/10.1007/s10584-020-02848-6

290. Palinkas, L.A. and M. Wong, 2020: Global climate change and mental health. *Current Opinion in Psychology*, **32**, 12–16. https://doi.org/10.1016/j.copsyc.2019.06.023

291. Clayton, S., 2020: Climate anxiety: Psychological responses to climate change. *Journal of Anxiety Disorders*, **74**, 102263. https://doi.org/10.1016/j.janxdis.2020.102263

292. Panu, P., 2020: Anxiety and the ecological crisis: An analysis of eco-anxiety and climate anxiety. *Sustainability*, **12** (19), 7836. https://doi.org/10.3390/su12197836

293. Espinel, Z., J.P. Kossin, S. Galea, A.S. Richardson, and J.M. Shultz, 2019: Forecast: Increasing mental health consequences from Atlantic hurricanes throughout the 21st century. *Psychiatric Services*, **70** (12), 1165–1167. https://doi.org/10.1176/appi.ps.201900273

294. Orengo-Aguayo, R., R.W. Stewart, M.A. Arellano, J.L. Suárez-Kindy, and J. Young, 2019: Disaster exposure and mental health among Puerto Rican youths after Hurricane Maria. *JAMA Network Open*, **2** (4), 192619. https://doi.org/10.1001/jamanetworkopen.2019.2619

295. Scaramutti, C., C.P. Salas-Wright, S.R. Vos, and S.J. Schwartz, 2019: The mental health impact of Hurricane Maria on Puerto Ricans in Puerto Rico and Florida. *Disaster Medicine and Public Health Preparedness*, **13** (1), 24–27. https://doi.org/10.1017/dmp.2018.151

296. Kunreuther, H.C., E.O. Michel-Kerjan, N.A. Doherty, M.F. Grace, R.W. Klein, and M.V. Pauly, 2009: *At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes*. The MIT Press, 440 pp. http://www.jstor.org/stable/j.ctt5hhn3h

297. Mileti, D., 1999: *Disasters by Design: A Reassessment of Natural Hazards in the United States*. Joseph Henry Press, Washington, DC, 371 pp. https://doi.org/10.17226/5782

298. Martinich, J. and A. Crimmins, 2019: Climate damages and adaptation potential across diverse sectors of the United States. *Nature Climate Change*, **9** (5), 397–404. https://doi.org/10.1038/s41558-019-0444-6

299. Grinsted, A., P. Ditlevsen, and J.H. Christensen, 2019: Normalized US hurricane damage estimates using area of total destruction, 1900–2018. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (48), 23942–23946. https://doi.org/10.1073/pnas.1912277116

300. Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D.J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser, 2017: Estimating economic damage from climate change in the United States. *Science*, **356** (6345), 1362–1369. https://doi.org/10.1126/science.aal4369

301. Bhattachan, A., M.D. Jurjonas, P.R. Morris, P.J. Taillie, L.S. Smart, R.E. Emanuel, and E.L. Seekamp, 2019: Linking residential saltwater intrusion risk perceptions to physical exposure of climate change impacts in rural coastal communities of North Carolina. *Natural Hazards*, **97** (3), 1277–1295. https://doi.org/10.1007/s11069-019-03706-0

302. Colburn, L.L., M. Jepson, C. Weng, T. Seara, J. Weiss, and J.A. Hare, 2016: Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. *Marine Policy*, **74**, 323–333. https://doi.org/10.1016/j.marpol.2016.04.030

303. Seara, T., M. Jepson, and M. McPherson, 2022: Community Climate Change Vulnerability in the South Atlantic, Florida Keys and Gulf of Mexico. NOAA Technical Memorandum NMFS-SEFSC-754. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Miami, FL, 40 pp. https://doi.org/10.25923/0wqe-3511

304. Pederson, N., A.R. Bell, T.A. Knight, C. Leland, N. Malcomb, K.J. Anchukaitis, K. Tackett, J. Scheff, A. Brice, B. Catron, W. Blozan, and J. Riddle, 2012: A long-term perspective on a modern drought in the American Southeast. *Environmental Research Letters*, **7** (1), 014034. https://doi.org/10.1088/1748-9326/7/1/014034

305. Raczynski, K. and J. Dyer, 2022: Variability of annual and monthly streamflow droughts over the southeastern United States. *Water*, **14** (23). https://doi.org/10.3390/w14233848

306. Sohn, J., 2011: Watering cities: Spatial analysis of urban water use in the southeastern United States. *Journal of Environmental Planning and Management*, **54** (10), 1351–1371. https://doi.org/10.1080/09640568.2011.575188

307. Sun, G., S.G. McNulty, J.A. Moore Myers, and E.C. Cohen, 2008: Impacts of multiple stresses on water demand and supply across the southeastern United States. *JAWRA Journal of the American Water Resources Association*, **44** (6), 1441–1457. https://doi.org/10.1111/j.1752-1688.2008.00250.x

308. Bolinger, B., 2019: How Drought Prone Is Your State? A Look at the Top States and Counties in Drought over the Last Two Decades. National Oceanic and Atmospheric Administration, National Integrated Drought Information System. https://www.drought.gov/news/how-drought-prone-your-state-look-top-states-and-counties-drought-over-last-two-decades

309. Engström, J., K. Jafarzadegan, and H. Moradkhani, 2020: Drought vulnerability in the United States: An integrated assessment. *Water*, **12** (7), 2033. https://doi.org/10.3390/w12072033

310. Alexandrov, V.A. and G. Hoogenboom, 2000: Vulnerability and adaptation assessments of agricultural crops under climate change in the southeastern USA. *Theoretical and Applied Climatology*, **67** (1), 45–63. https://doi.org/10.1007/s007040070015

311. Shortridge, J., 2019: Observed trends in daily rainfall variability result in more severe climate change impacts to agriculture. *Climatic Change*, **157** (3), 429–444. https://doi.org/10.1007/s10584-019-02555-x

312. Castillo, F., A.M. Mora, G.L. Kayser, J. Vanos, C. Hyland, A.R. Yang, and B. Eskenazi, 2021: Environmental health threats to Latino migrant farmworkers. *Annual Review of Public Health*, **42** (1), 257–276. https://doi.org/10.1146/annurev-publhealth-012420-105014

313. Zhang, Y. and D.T. Shindell, 2021: Costs from labor losses due to extreme heat in the USA attributable to climate change. *Climatic Change*, **164** (3), 35. https://doi.org/10.1007/s10584-021-03014-2

314. DOT, 2021: Climate Action Plan: Revitalizing Efforts to Bolster Adaptation & Increase Resilience. U.S. Department of Transportation, Office of the Secretary of Transportation, Washington, DC. https://rosap.ntl.bts.gov/view/dot/66379

315. Burton, M., J. Camp, C. Philip, and L. Bray, 2017: The Impacts of Unscheduled Lock Outages. National Waterways Foundation and U.S. Maritime Administration. https://www.nationalwaterwaysfoundation.org/file/2/low%20res%20lock%20outage%20nwf_final_report%202017.pdf

316. Pinkley, S.G.N., K.M. Sullivan, B.R. Runkle, H.T. Bui, J. Khatamov, J. Camp, K. Turner, and N. Laning, 2021: Informing Post-Disaster Restoration Through Modeling Interdependent Agriculture and Transportation Networks. Maritime Transportation Research and Education Center. https://rosap.ntl.bts.gov/view/dot/61007

317. Neumann, J.E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich, 2021: Climate effects on US infrastructure: The economics of adaptation for rail, roads, and coastal development. *Climatic Change*, **167** (3), 44. https://doi.org/10.1007/s10584-021-03179-w

318. Ghadge, A., H. Wurtmann, and S. Seuring, 2020: Managing climate change risks in global supply chains: A review and research agenda. *International Journal of Production Research*, **58** (1), 44–64. https://doi.org/10.1080/00207543.2019.1629670

319. Camp, J., M. Abkowitz, G. Hornberger, L. Benneyworth, and J.C. Banks, 2013: Climate change and freight-transportation infrastructure: Current challenges for adaptation. *Journal of Infrastructure Systems*, **19** (4), 363–370. https://doi.org/10.1061/(asce)is.1943-555x.0000151

320. Fant, C., B. Boehlert, K. Strzepek, P. Larsen, A. White, S. Gulati, Y. Li, and J. Martinich, 2020: Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure. *Energy*, **195**, 116899. https://doi.org/10.1016/j.energy.2020.116899

321. Larsen, P.H., B. Boehlert, J. Eto, K. Hamachi-LaCommare, J. Martinich, and L. Rennels, 2018: Projecting future costs to U.S. electric utility customers from power interruptions. *Energy*, **147**, 1256–1277. https://doi.org/10.1016/j.energy.2017.12.081

322. Polansek, T., 2021: US Coast Guard shuts part of lower Mississippi River as bridge cracks. *Reuters*, May 12, 2021. https://www.reuters.com/world/us/coast-guard-shuts-portion-lower-mississippi-river-due-bridge-crack-2021-05-12/

323. Prida, A., 2021: How Does Climate Change Affect Inland Waterway Transport in the Mississippi river? AXA Climate. https://www.climate.axa/articles/how-does-climate-change-affect-inland-waterway-transport-in-the-mississippi-river

324. Nakano, K., 2021: Risk assessment for adaptation to climate change in the international supply chain. *Journal of Cleaner Production*, **319**, 128785. https://doi.org/10.1016/j.jclepro.2021.128785

325. Godde, C.M., D. Mason-D'Croz, D.E. Mayberry, P.K. Thornton, and M. Herrero, 2021: Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, **28**, 100488. https://doi.org/10.1016/j.gfs.2020.100488

326. BTS, 2022: Low Water on the Mississippi Slows Critical Freight Flows. U.S. Department of Transportation, Bureau of Transportation Statistics, accessed April 27, 2023. https://www.bts.gov/data-spotlight/low-water-mississippi-slows-critical-freight-flows

327. CoFiRES, 2023: Characterizing and Managing the Financial Risks of Drought Along the Mississippi River. University of North Carolina, Gillings School of Global Public Health, Center on Financial Risk in Environmental Systems, accessed May 18, 2023. https://sph.unc.edu/cfres/mississippi-river/

328. Neidell, M., J.G. Zivin, M. Sheahan, J. Willwerth, C. Fant, M. Sarofim, and J. Martinich, 2021: Temperature and work: Time allocated to work under varying climate and labor market conditions. *PLoS ONE*, **16** (8), 0254224. https://doi.org/10.1371/journal.pone.0254224

329. Rode, A., R.E. Baker, T. Carleton, A. D'Agostino, M. Delgado, T. Foreman, D.R. Gergel, M. Greenstone, T. Houser, S. Hsiang, A. Hultgren, A. Jina, R.E. Kopp, S.B. Malevich, K.E. McCusker, I. Nath, M. Pecenco, J. Rising, and J. Yuan, 2022: Labor Disutility in a Warmer World: The Impact of Climate Change on the Global Workforce. Social Science Research Network, 96 pp. https://doi.org/10.2139/ssrn.4221478

330. Karthick, S., S. Kermanshachi, B. Rouhanizadeh, and M. Namian, 2021: Short- and long-term health challenges of transportation workforce due to extreme weather conditions. In: *Tran-SET 2021*. American Society of Civil Engineers, 39–51. https://doi.org/10.1061/9780784483787.005

331. EIA, 2022: Gulf of Mexico Fact Sheet. U.S. Energy Information Administration, Washington, DC. http://www.eia.gov/special/gulf_of_mexico/

332. Burkett, V., 2011: Global climate change implications for coastal and offshore oil and gas development. *Energy Policy*, **39** (12), 7719–7725. https://doi.org/10.1016/j.enpol.2011.09.016

333. Cruz, A.M. and E. Krausmann, 2008: Damage to offshore oil and gas facilities following Hurricanes Katrina and Rita: An overview. *Journal of Loss Prevention in the Process Industries*, **21** (6), 620–626. https://doi.org/10.1016/j.jlp.2008.04.008

334. Coleman, N., A. Esmalian, and A. Mostafavi, 2020: Equitable resilience in infrastructure systems: Empirical assessment of disparities in hardship experiences of vulnerable populations during service disruptions. *Natural Hazards Review*, **21** (4), 04020034. https://doi.org/10.1061/(asce)nh.1527-6996.0000401

335. Sussman, F.G. and J.R. Freed, 2008: Adapting to Climate Change: A Business Approach. Pew Center on Global Climate Change, Arlington, VA. https://www.pewtrusts.org/~/media/legacy/uploadedfiles/wwwpewtrustsorg/reports/global_warming/businessadaptationpdf.pdf

336. Louie, E.P. and J.M. Pearce, 2016: Retraining investment for U.S. transition from coal to solar photovoltaic employment. *Energy Economics*, **57**, 295–302. https://doi.org/10.1016/j.eneco.2016.05.016

337. Carley, S. and D.M. Konisky, 2020: The justice and equity implications of the clean energy transition. *Nature Energy*, **5** (8), 569–577. https://doi.org/10.1038/s41560-020-0641-6

338. Tomer, A., J. Kane, and C. George, 2021: How Renewable Energy Jobs Can Uplift Fossil Fuel Communities and Remake Climate Politics. The Brookings Institution. https://www.brookings.edu/research/how-renewable-energy-jobs-can-uplift-fossil-fuel-communities-and-remake-climate-politics/

339. Abraham, J., 2017: Just transitions for the miners: Labor environmentalism in the Ruhr and Appalachian coalfields. *New Political Science*, **39** (2), 218–240. https://doi.org/10.1080/07393148.2017.1301313

340. Chesmore, G., R. Starr, R. Van Hoeck, and M. Ward, 2021: The crisis of US coal communities: Strategies for a just transition to renewable energy. *Journal of Science Policy & Governance*, **18** (2). https://doi.org/10.38126/jspg180202

341. Becker, W.S. and B. McKibben, 2021: *The Creeks Will Rise: People Coexisting with Floods*. Chicago Review Press, 368 pp. https://www.chicagoreviewpress.com/creeks-will-rise--the-products-9781682752753.php

342. ERS, 2022: Ag and Food Sectors and the Economy. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/ag-and-food-sectors-and-the-economy/

343. NASS, 2019: 2017 Census of Agriculture: United States Summary and State Data. AC-17-A-51. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/agcensus/2017/index.php

344. Karakoc, D.B., J. Wang, and M. Konar, 2022: Food flows between counties in the United States from 2007 to 2017. *Environmental Research Letters*, **17** (3), 034035. https://doi.org/10.1088/1748-9326/ac5270

345. Walker, R.E., C.R. Keane, and J.G. Burke, 2010: Disparities and access to healthy food in the United States: A review of food deserts literature. *Health & Place*, **16** (5), 876–884. https://doi.org/10.1016/j.healthplace.2010.04.013

346. DeGaetano, A.T. and R.J. Allen, 2002: Trends in twentieth-century temperature extremes across the United States. *Journal of Climate*, **15** (22), 3188–3205. DOI:10.1175/1520-0442(2002)015<3188:titcte>2.0.co;2. https://journals.ametsoc.org/view/journals/clim/15/22/1520-0442_2002_015_3188_titcte_2.0.co_2.xml

347. Bernabucci, U., 2019: Climate change: Impact on livestock and how can we adapt. *Animal Frontiers: The Review Magazine of Animal Agriculture*, **9** (1), 3–5. https://doi.org/10.1093/af/vfy039

348. Parker, L.E. and J.T. Abatzoglou, 2019: Warming winters reduce chill accumulation for peach production in the southeastern United States. *Climate*, **7** (8), 94. https://doi.org/10.3390/cli7080094

349. EPA, 2016: Climate Change Indicators: Length of Growing Season. U.S. Environmental Protection Agency. https://www.epa.gov/climate-indicators/climate-change-indicators-length-growing-season

350. Schaarschmidt, S., L.M.F. Lawas, J. Kopka, S.V.K. Jagadish, and E. Zuther, 2021: Physiological and molecular attributes contribute to high night temperature tolerance in cereals. *Plant, Cell & Environment*, **44** (7), 2034–2048. https://doi.org/10.1111/pce.14055

351. Apurv, T. and X. Cai, 2021: Regional drought risk in the contiguous United States. *Geophysical Research Letters*, **48** (5), 2020GL092200. https://doi.org/10.1029/2020gl092200

352. Ficklin, D.L., J.T. Maxwell, S.L. Letsinger, and H. Gholizadeh, 2015: A climatic deconstruction of recent drought trends in the United States. *Environmental Research Letters*, **10** (4), 044009. https://doi.org/10.1088/1748-9326/10/4/044009

353. Rind, D., R. Goldberg, J. Hansen, C. Rosenzweig, and R. Ruedy, 1990: Potential evapotranspiration and the likelihood of future drought. *Journal of Geophysical Research: Atmospheres*, **95** (D7), 9983–10004. https://doi.org/10.1029/jd095id07p09983

354. Leeper, R.D., R. Bilotta, B. Petersen, C.J. Stiles, R. Heim, B. Fuchs, O.P. Prat, M. Palecki, and S. Ansari, 2022: Characterizing U.S. drought over the past 20 years using the U.S. Drought Monitor. *International Journal of Climatology*, **42** (12), 6616–6630. https://doi.org/10.1002/joc.7653

355. Apurv, T., X. Cai, and X. Yuan, 2019: Influence of internal variability and global warming on multidecadal changes in regional drought severity over the continental United States. *Journal of Hydrometeorology*, **20** (3), 411–429. https://doi.org/10.1175/jhm-d-18-0167.1

356. Crystal-Ornelas, R., E.J. Hudgins, R.N. Cuthbert, P.J. Haubrock, J. Fantle-Lepczyk, E. Angulo, A.M. Kramer, L. Ballesteros-Mejia, B. Leroy, B. Leung, E. López-López, C. Diagne, and F. Courchamp, 2021: Economic costs of biological invasions within North America. *NeoBiota*, **67**, 485–510. https://doi.org/10.3897/neobiota.67.58038

357. Paini, D.R., A.W. Sheppard, D.C. Cook, P.J. De Barro, S.P. Worner, and M.B. Thomas, 2016: Global threat to agriculture from invasive species. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (27), 7575–7579. https://doi.org/10.1073/pnas.1602205113

358. Armal, S., N. Devineni, and R. Khanbilvardi, 2018: Trends in extreme rainfall frequency in the contiguous United States: Attribution to climate change and climate variability modes. *Journal of Climate*, **31** (1), 369–385. https://doi.org/10.1175/jcli-d-17-0106.1

359. Bartels, R.J., A.W. Black, and B.D. Keim, 2020: Trends in precipitation days in the United States. *International Journal of Climatology*, **40** (2), 1038–1048. https://doi.org/10.1002/joc.6254

360. Brown, V.M., B.D. Keim, and A.W. Black, 2019: Climatology and trends in hourly precipitation for the southeast United States. *Journal of Hydrometeorology*, **20** (8), 1737–1755. https://doi.org/10.1175/jhm-d-19-0004.1

361. Brown, V.M., B.D. Keim, and A.W. Black, 2020: Trend analysis of multiple extreme hourly precipitation time series in the southeastern United States. *Journal of Applied Meteorology and Climatology*, **59** (3), 427–442. https://doi.org/10.1175/jamc-d-19-0119.1

362. Kossin, J.P., 2018: A global slowdown of tropical-cyclone translation speed. *Nature*, **558** (7708), 104–107. https://doi.org/10.1038/s41586-018-0158-3

363. Harris, A.R., E.N. Fidan, N.G. Nelson, R.E. Emanuel, T. Jass, S. Kathariou, J. Niedermeyer, M. Sharara, F.L. de los Reyes, D.A. Riveros-Iregui, and J.R. Stewart, 2021: Microbial contamination in environmental waters of rural and agriculturally-dominated landscapes following Hurricane Florence. *ACS ES&T Water*, **1** (9), 2012–2019. https://doi.org/10.1021/acsestwater.1c00103

364. Paul, M.J., R. Coffey, J. Stamp, and T. Johnson, 2019: A review of water quality responses to air temperature and precipitation changes 1: Flow, water temperature, saltwater intrusion. *JAWRA Journal of the American Water Resources Association*, **55** (4), 824–843. https://doi.org/10.1111/1752-1688.12710

365. Izaguirre, C., I.J. Losada, P. Camus, J.L. Vigh, and V. Stenek, 2021: Climate change risk to global port operations. *Nature Climate Change*, **11** (1), 14–20. https://doi.org/10.1038/s41558-020-00937-z

366. Markolf, S.A., C. Hoehne, A. Fraser, M.V. Chester, and B.S. Underwood, 2019: Transportation resilience to climate change and extreme weather events—Beyond risk and robustness. *Transport Policy*, **74**, 174–186. https://doi.org/10.1016/j.tranpol.2018.11.003

367. Verschuur, J., E.E. Koks, and J.W. Hall, 2020: Port disruptions due to natural disasters: Insights into port and logistics resilience. *Transportation Research Part D: Transport and Environment*, **85**, 102393. https://doi.org/10.1016/j.trd.2020.102393

368. Benevolenza, M.A. and L. DeRigne, 2019: The impact of climate change and natural disasters on vulnerable populations: A systematic review of literature. *Journal of Human Behavior in the Social Environment*, **29** (2), 266–281. https://doi.org/10.1080/10911359.2018.1527739

369. Craig, C.A., S. Feng, and S. Gilbertz, 2019: Water crisis, drought, and climate change in the southeast United States. *Land Use Policy*, **88**, 104110. https://doi.org/10.1016/j.landusepol.2019.104110

370. Harris, G., 2020: Beginning, minority, and other underserved farmers and ranchers in the 2017 Census of Agriculture. *Agricultural Outlook Forum*. U.S. Department of Agriculture. https://doi.org/10.22004/ag.econ.320929

371. Furman, C., C. Roncoli, W. Bartels, M. Boudreau, H. Crockett, H. Gray, and G. Hoogenboom, 2014: Social justice in climate services: Engaging African American farmers in the American South. *Climate Risk Management*, **2**, 11–25. https://doi.org/10.1016/j.crm.2014.02.002

372. Ali, C., 2021: *Farm Fresh Broadband: The Politics of Rural Connectivity*. MIT Press, 306 pp. https://mitpress.mit.edu/9780262543064/farm-fresh-broadband/

373. Lal, P., J.R.R. Alavalapati, and E.D. Mercer, 2011: Socio-economic impacts of climate change on rural United States. *Mitigation and Adaptation Strategies for Global Change*, **16** (7), 819–844. https://doi.org/10.1007/s11027-011-9295-9

374. Leslie, I.S. and M.M. White, 2018: Ch. 19. Race and Food: Agricultural resistance in U.S. history. In: *Handbook of the Sociology of Racial and Ethnic Relations*. Batur, P. and J.R. Feagin, Eds. Springer, Cham, Switzerland, 347–364. https://doi.org/10.1007/978-3-319-76757-4_19

375. Quaye, F., D. Nadolnyak, and V. Hartarska, 2018: Climate change impacts on farmland values in the southeast United States. *Sustainability*, **10** (10), 3426. https://doi.org/10.3390/su10103426

376. Holka, M., J. Kowalska, and M. Jakubowska, 2022: Reducing carbon footprint of agriculture—Can organic farming help to mitigate climate change? *Agriculture*, **12** (9). https://doi.org/10.3390/agriculture12091383

377. Jouzi, Z., H. Azadi, F. Taheri, K. Zarafshani, K. Gebrehiwot, S. Van Passel, and P. Lebailly, 2017: Organic farming and small-scale farmers: Main opportunities and challenges. *Ecological Economics*, **132**, 144–154. https://doi.org/10.1016/j.ecolecon.2016.10.016

378. Flörke, M., C. Schneider, and R.I. McDonald, 2018: Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, **1** (1), 51–58. https://doi.org/10.1038/s41893-017-0006-8

379. Schlef, K.E., S. Steinschneider, and C.M. Brown, 2018: Spatiotemporal impacts of climate and demand on water supply in the Apalachicola-Chattahoochee-Flint Basin. *Journal of Water Resources Planning and Management*, **144** (2), 05017020. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000865

380. Krayenhoff, E.S., M. Moustaoui, A.M. Broadbent, V. Gupta, and M. Georgescu, 2018: Diurnal interaction between urban expansion, climate change and adaptation in US cities. *Nature Climate Change*, **8** (12), 1097–1103. https://doi.org/10.1038/s41558-018-0320-9

381. Napton, D.E., R.F. Auch, R. Headley, and J.L. Taylor, 2010: Land changes and their driving forces in the southeastern United States. *Regional Environmental Change*, **10** (1), 37–53. https://doi.org/10.1007/s10113-009-0084-x

382. Changnon, S.A., 1989: The 1988 drought, barges, and diversion. *Bulletin of the American Meteorological Society*, **70** (9), 1092–1104. DOI:10.1175/1520-0477(1989)070<1092:tdbad>2.0.co;2. https://journals.ametsoc.org/view/journals/bams/70/9/1520-0477_1989_070_1092_tdbad_2_0_co_2.xml

383. Kemp, G.P., C.S. Willson, J.D. Rogers, K.A. Westphal, and S.A. Binselam, 2014: Adapting to change in the lowermost Mississippi River: Implications for navigation, flood control and restoration of the delta ecosystem. In: *Perspectives on the Restoration of the Mississippi Delta: The Once and Future Delta.* Day, J.W., G.P. Kemp, A.M. Freeman, and D.P. Muth, Eds. Springer, Dordrecht, Netherlands, 51–84. https://doi.org/10.1007/978-94-017-8733-8_5

384. Balbus, J.M. and C. Malina, 2009: Identifying vulnerable subpopulations for climate change health effects in the United States. *Journal of Occupational and Environmental Medicine*, **51** (1), 33–37. https://doi.org/10.1097/jom.0b013e318193e12e

385. Porfirio, L.L., D. Newth, J.J. Finnigan, and Y. Cai, 2018: Economic shifts in agricultural production and trade due to climate change. *Palgrave Communications*, **4** (1), 1–9. https://doi.org/10.1057/s41599-018-0164-y

386. Balafoutis, A., B. Beck, S. Fountas, J. Vangeyte, T. Van der Wal, I. Soto, M. Gómez-Barbero, A. Barnes, and V. Eory, 2017: Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. *Sustainability*, **9** (8), 1339. https://doi.org/10.3390/su9081339

387. Kaye, J.P. and M. Quemada, 2017: Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for Sustainable Development*, **37** (1), 1–17. https://doi.org/10.1007/s13593-016-0410-x

388. Kladivko, E.J., T.C. Kaspar, D.B. Jaynes, R.W. Malone, J. Singer, X.K. Morin, and T. Searchinger, 2014: Cover crops in the upper midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River Basin. *Journal of Soil and Water Conservation*, **69** (4), 279–291. https://doi.org/10.2489/jswc.69.4.279

389. Sarrantonio, M. and E. Gallandt, 2003: The role of cover crops in North American cropping systems. *Journal of Crop Production*, **8** (1–2), 53–74. https://doi.org/10.1300/j144v08n01_04

390. Grey, T.L., K. Rucker, T.M. Webster, and X. Luo, 2016: High-density plantings of olive trees are tolerant to repeated applications of indaziflam. *Weed Science*, **64** (4), 766–771. https://doi.org/10.1614/ws-d-16-00025.1

391. Hanly, M. and S. Davis, 2010: History of Olive Growing in Georgia: The Past and Future of Olive Tree Production in Georgia. Georgia Olive Growers Association. http://georgiaolivegrowers.com/resources-research/history/

392. Jacobs, J. and G. Krewer, 2009: An Early Look at Olives in Georgia. The University of Georgia. https://extension.uga.edu/about/our-impact/impact-stories/impact-statement/2393/an-early-look-at-olives-in-georgia.html

393. Nesbitt, M.L., R.C. Ebel, and W.A. Dozier Jr., 2008: Production practices for satsuma mandarins in the southeastern United States. *HortScience*, **43** (2), 290–292. https://doi.org/10.21273/hortsci.43.2.290

394. Davis, M., 2020: U.S. Fish and Wildlife Service Programmatic Environmental Assessment for Use of Genetically Engineered Agricultural Crops for Natural Resource Management on National Wildlife Refuges in the Southeastern United States. U.S. Department of Interior, U.S. Fish and Wildlife Service, Atlanta, GA. https://ecos.fws.gov/servcat/downloadfile/171732

395. Kovak, E., D. Blaustein-Rejto, and M. Qaim, 2022: Genetically modified crops support climate change mitigation. *Trends in Plant Science*, **27** (7), 627–629. https://doi.org/10.1016/j.tplants.2022.01.004

396. Lesk, C., E. Coffel, J. Winter, D. Ray, J. Zscheischler, S.I. Seneviratne, and R. Horton, 2021: Stronger temperature–moisture couplings exacerbate the impact of climate warming on global crop yields. *Nature Food*, **2** (9), 683–691. https://doi.org/10.1038/s43016-021-00341-6

397. Seifert, C.A. and D.B. Lobell, 2015: Response of double cropping suitability to climate change in the United States. *Environmental Research Letters*, **10** (2), 024002. https://doi.org/10.1088/1748-9326/10/2/024002

398. Nabhan, G.P. and J.L. Carr, Eds., 1994: *Ironwood: An Ecological and Cultural Keystone of the Sonoran Desert.* University of Chicago Press, 92 pp. https://press.uchicago.edu/ucp/books/book/distributed/I/bo3634046.html

399. Noss, R.F., E.T. LaRoe III, and J.M. Scott, 1995: Endangered Ecosystems of the United States: A Preliminary Assessment of Loss and Degradation. Biological Report 28. U.S. Department of the Interior, National Biological Service, Washington, DC. https://ecos.fws.gov/servcat/downloadfile/101448?reference=61075

400. Anderson, M.K. and T. Oakes, 2011: Plant Guide for Giant Cane *Arundinaria gigantea*. U.S. Department of Agriculture, Natural Resources Conservation Service, National Plant Data Team, Greensboro, NC. https://plants.sc.egov.usda.gov/documentlibrary/plantguide/pdf/cs_argi.pdf

401. McKenzie, E.R., 2021: Indigenous Approaches to Rivercane Restoration Workshop. U.S Army Corps of Engineers, 38 pp. https://www.spa.usace.army.mil/portals/16/docs/tntcx/misc/feb_2022_rr%20workshop%20report_final.pdf?ver=8b900adld-cpycs2bh4x_q%3d%3d

402. Michaux, F.A. and B. Lambert, 1805: *Travels to the Westward of the Allegany Mountains, in the States of Ohio, Kentucky, and Tennessee, and Return to Charlestown, Through the Upper Carolinas; Containing Details on the Present State of Agriculture and the Natural Production of These Countries; As Well as Information Relative to the Commercial Connections of These States with Those Situated to the Eastward of the Mountains and with Lower Louisiana. Undertaken in the Year X, 1802, Under the Auspices of His Excellency M. Chaptal, Minister of the Interior. With a Very Correct Map of the States in the Centre, West and South of the United States*. Mawman, J., Ed., London, UK, 350 pp. [Print].

403. Aranzazu Lascurain (Author), September 8, 2022: Oral communication/email communication with Mitzi Reed, Mississippi Band of Choctaw Indians.

404. Platt, S.G., C.G. Brantley, and T.R. Rainwater, 2001: Canebrake fauna: Wildlife diversity in a critically endangered ecosystem. *Journal of the Elisha Mitchell Scientific Society*, **117** (1), 1–19. http://www.jstor.org/stable/24335363

405. Schoonover, J.E., K.W.J. Williard, J.J. Zaczek, J.C. Mangun, and A.D. Carver, 2006: Agricultural sediment reduction by giant cane and forest riparian buffers. *Water, Air, and Soil Pollution*, **169** (1), 303–315. https://doi.org/10.1007/s11270-006-3111-2

406. Adam Griffith (Technical Contributor), May 24, 2022: Oral communication/email communication with Mary W. Thompson, Eastern Band of Cherokee Indians.

407. Schramm, P.J., C.L. Brown, S. Saha, K.C. Conlon, A.P. Manangan, J.E. Bell, and J.J. Hess, 2021: A systematic review of the effects of temperature and precipitation on pollen concentrations and season timing, and implications for human health. *International Journal of Biometeorology*, **65** (10), 1615–1628. https://doi.org/10.1007/s00484-021-02128-7

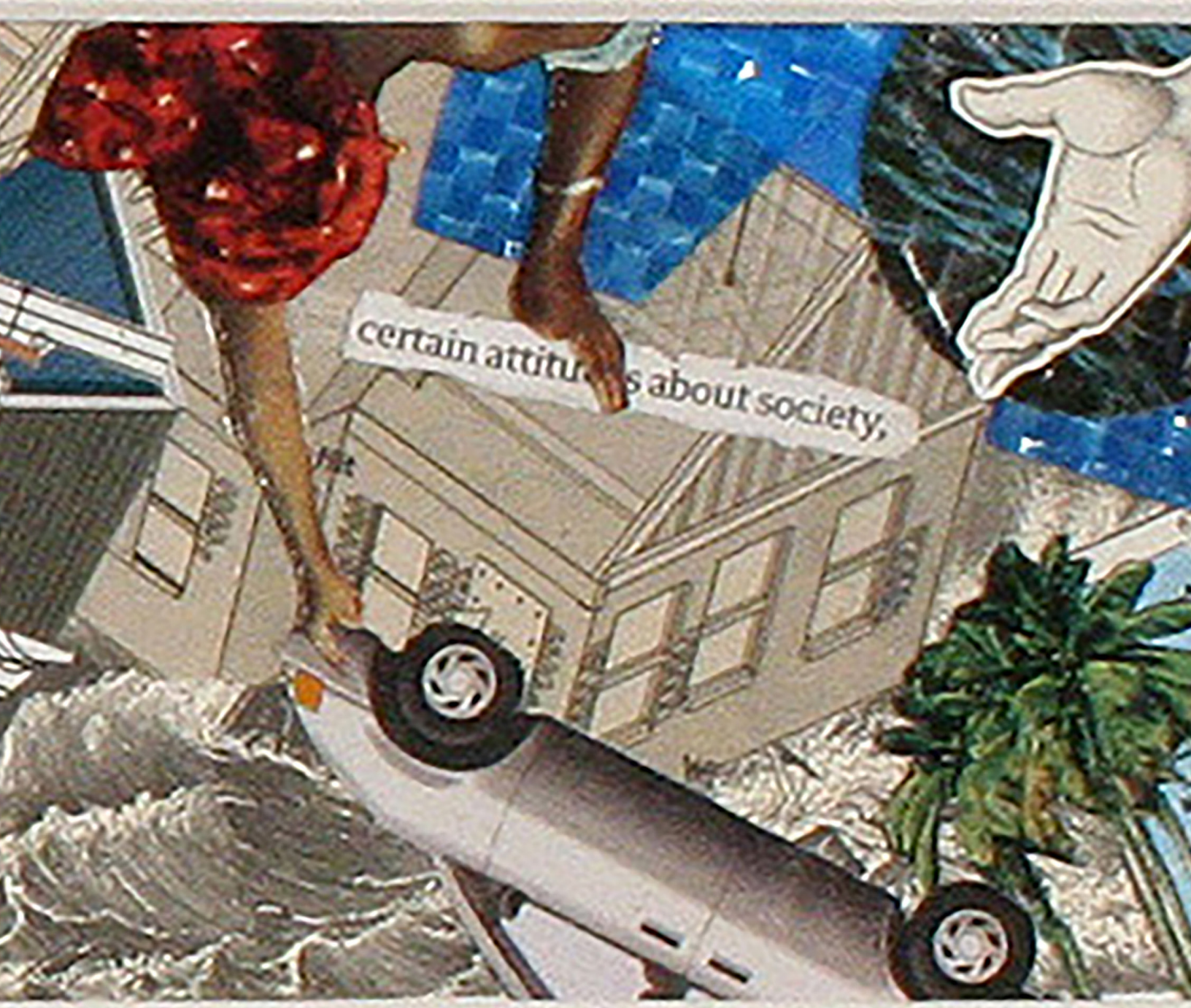
408. Eck, M.A., A.R. Murray, A.R. Ward, and C.E. Konrad, 2020: Influence of growing season temperature and precipitation anomalies on crop yield in the southeastern United States. *Agricultural and Forest Meteorology*, **291**, 108053. https://doi.org/10.1016/j.agrformet.2020.108053

409. Gordemer, B., 2021: Rising sea levels threaten the lives and livelihood of those on a fragile U.S. coast. NPR, November 7, 2021. https://www.npr.org/2021/11/07/1051529051/rising-sea-levels-climate-change-south-carolina-coast

410. Crespi, J., C. Hart, C. Pudenz, L. Schulz, O. Wongpiyabovorn, and W. Zhang, 2022: An Examination of Recent Fertilizer Price Changes. Staff Report 22-SR 117. Iowa State University, Center for Agricultural and Rural Development, Ames, IA. https://doi.org/10.13140/rg.2.2.24806.70720

Fifth National Climate Assessment: Chapter 23

# US Caribbean



# Chapter 23. US Caribbean

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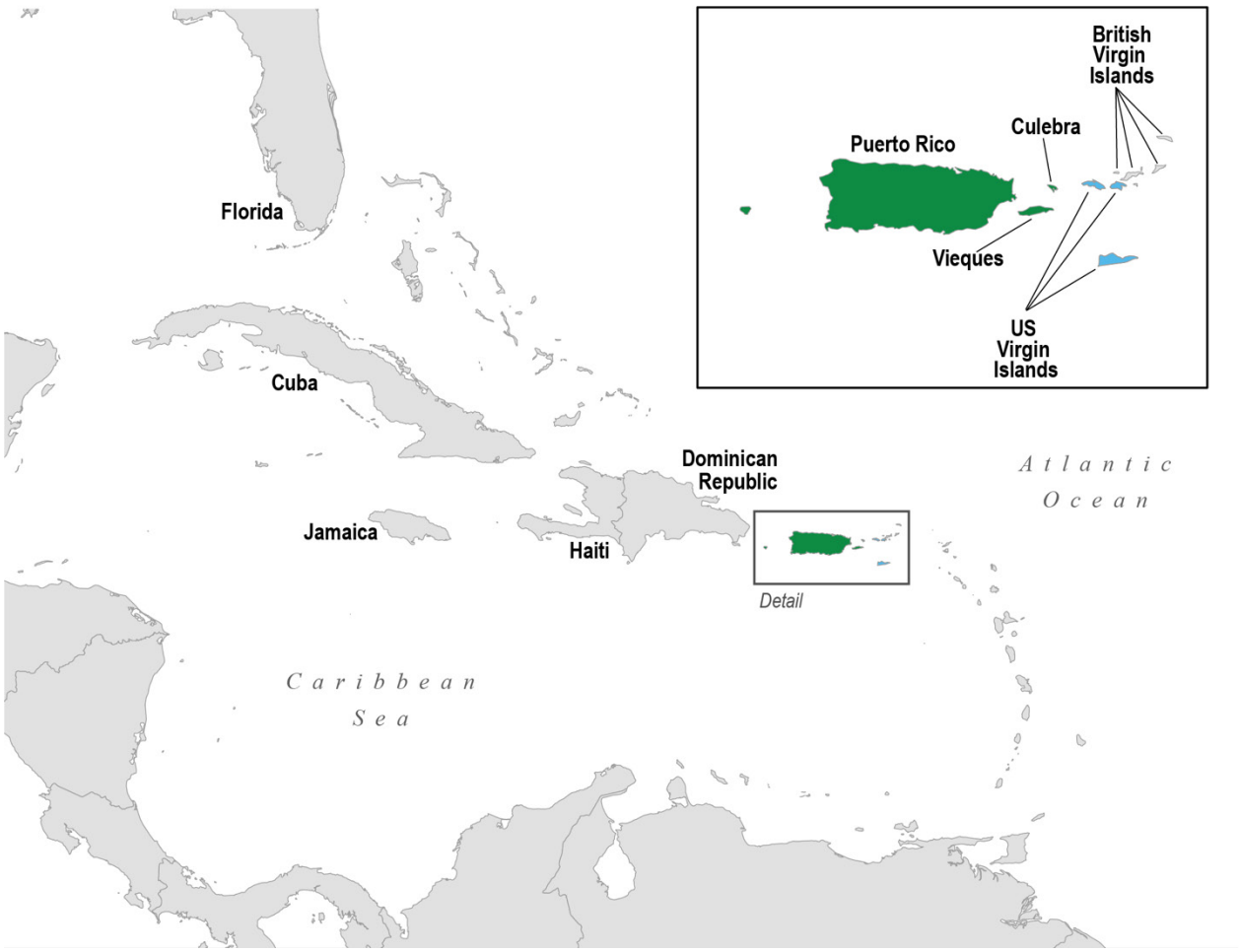
# Introduction

The US Caribbean comprises Puerto Rico (PR) and the US Virgin Islands (USVI; Figure 23.1). Both are US territories, and people born there acquire US citizenship by birth. The USVI is home to about 87,000 US citizens (Table 23.1).[1] The USVI has a majority Black population and a mix of English-, Spanish-, and Creole-speaking communities. Puerto Rico (which includes the inhabited islands of Vieques and Culebra) has a population of around 3 million US citizens who are predominantly Hispanic- or Latino-Spanish speakers. Communities in both territories are now the source of significant migration to the US mainland.[2,3,4,5,6]

## The US Caribbean




**The US Caribbean region in the Fifth National Climate Assessment consists of Puerto Rico and the US Virgin Islands.**

**Figure 23.1.** The map shows the location of Puerto Rico and the US Virgin Islands in the Caribbean Basin. The inset shows the main island of Puerto Rico (green; the two municipal islands of Vieques and Culebra are shown to the east and Mona Island to the west) and the US Virgin Islands (yellow; St. Thomas and St. John to the north and St. Croix to the south). Figure credit: University of Puerto Rico, NOAA NCEI, and CISESS NC.

The USVI and PR share a geographic region. Both are populated by groups that the US government considers minorities, and both face enormous socioeconomic challenges. At the same time, they have different socioeconomic, geopolitical, and climate realities. They are also quite different in scale, governance, and demographics (Table 23.1). Island residents have learned to cope with adversity due to centuries of unfavorable social inequality, colonial policies, and extreme climate events.[7]

**Table 23.1. Geography of US Caribbean Territories**

The sociodemographic profiles of Puerto Rico and the US Virgin Islands are grounded in long histories of colonization, systemic inequality, and parallel historical backgrounds with deeply rooted Indigenous traditions. These territories are facing similar climate-related hazards that are compounded by shrinking economies, aging populations, and ineffective government structures. Sources: Median household income from US Department of Housing and Urban Development;[8] other data from US Census Bureau.[6]

| Category | Puerto Rico | US Virgin Islands |
|---|---|---|
| **Population Living Below Poverty Level (US average: 11.4%)** | 43.5% | 18.4% |
| **Main Island(s) Surface Area** | 3,515 square miles | St. Thomas: 32 square miles<br>St. John: 20 square miles<br>St. Croix: 81 square miles |
| **Total Population** | 3,075,000* | St. Thomas: 42,261<br>St. John: 3,881<br>St. Croix: 41,004<br>Total: 87,146 |
| **Principal Language** | Spanish | English |
| **Urban Population** | 93% | 96.3% |
| **Rural Population** | 7% | 3.7% |
| **Race and Ethnicity** | 98.7% Hispanic or Latino**<br>(US: 18.5% Hispanic or Latino) | 76% Black (Afro-Caribbean)<br>(US: 13.4% Black or African American) |
| **Median Household Income (in 2020 dollars; US average $67,521)** | $20,539 | $37,254 |
| **Population Change 2010–2020** | –17.4% | –18.1% |
| **Government** | 1 governor<br>27 senators<br>51 representatives<br>78 mayors/municipalities<br>1 non-voting member of the US House of Representatives | 1 governor<br>15 senators (7 each district, 1 at-large)<br>No representatives<br>No mayors<br>1 non-voting member of the US House of Representatives |

*2020 Post-Enumeration Surveys.[9] **Although "Hispanic or Latino" is the official US Census category, it does not capture the racial and ethnic diversity of PR, the Caribbean, or Latin America. The official US Census definition for "Hispanic or Latino" refers to a person of Cuban, Mexican, Puerto Rican, South or Central American, or other Spanish cultural origin regardless of race. This definition is meant to cover all Spanish-speaking cultures.

These islands are particularly vulnerable to extreme weather events that are being exacerbated by human-driven climate change, and there is increased potential for impacts because people, cities, and critical infrastructure are often located in the most vulnerable locations.[10,11,12] Extreme weather is triggering cascading, ongoing crises and highlighting political divides, which shape response and recovery efforts. At the same time, these events are revealing grassroots organizational capacities typically ignored by national- or regional-scale discourses regarding vulnerability and resilience.[13,14] A changing climate in the Caribbean highlights the interdependencies of critical infrastructure systems. In addition, climate change threatens

the preservation of heritage, particularly tangible heritage both on land and underwater.[15] In addition to catastrophic failures caused by powerful hurricanes, the impacts of extreme events in many places in the Caribbean are exacerbated by intangible factors that undermine the foundations of strong communities and functional ecosystems. Post-disaster recovery is particularly complex in the US Caribbean because of diverse cultural practices, complicated governance structures, and uneven access to information and resources, sometimes referred to as differential social vulnerability (Box 23.1).

The absence of adequate governmental response to climate change and extreme events, coupled with a long history of political marginalization, has catalyzed the rise of community-based organizations that are pursuing sustainable development efforts on their own.[13]

## Box 23.1. Differential Vulnerabilities in the US Caribbean

Impacts of climate change on US Caribbean societies must be understood in the context of the social and historical processes that shape identity and exposure (see Chapter 20 for a detailed explanation of these concepts and the links to justice). Not everyone is equally impacted by climate change. Social vulnerability is a multidimensional process affected by social, political, and economic forces interacting from local to international scales.[16] In the US Caribbean, social vulnerability and social determinants of health are best viewed within a systemic risk framework and are at least partially influenced by the following:

- *Culture*: Broad ethnic diversity, different economic backgrounds, and deep historical traumas linked to colonization and struggle characterize the US Caribbean. These backgrounds shape locally relevant worldviews, risk-perception, decision-making, and adaptation and mitigation strategies. Perception of and response to climate risks include local and Traditional Ecological Knowledge and long-term memory of disasters that might or might not be transferable within or between islands (Ch. 20).

- *Access to resources*: High poverty indices and sharp social stratification, together with growing gentrification, migration, displacement, accumulated impacts from past disasters, and concerns linked to human health, influence access to resources—from economic to material objects—that could be used to lessen risks and prepare for adaptation. Aside from economic resources, access to natural resources is affected by the cumulative effects of human activities over time. In the Caribbean, for example, years of Indigenous agricultural practices, colonial plantation systems, and industrialization have contributed to reduced biodiversity, loss of forest cover, soil depletion, unstable slopes, and degraded marine ecosystems, which converge to heighten the severity of risks (Chs. 17, 18).

- *Access to information*: Climate data are often available only on scales that are too large for the needs of relatively small islands with very wide microclimatic diversity. Other barriers to accessing information include language (Spanish and English are the principal languages of PR and the USVI, respectively), educational barriers, poverty, growing indices of illiteracy, and distrust in official entities.

- *Governance*: The political relationship between the US Caribbean territories and the Federal Government affects the ability and capacity for local action. Other formal and informal systems of local governance also affect action, including grassroots leadership, local nongovernmental organizations, and religious organizations.

- *Puerto Rico's fiscal and economic situation:* The prolonged and deep contraction of Puerto Rico's economy since 2006, coupled with the fiscal crisis and the Puerto Rico government's bankruptcy, resulted in significant cutbacks in government institutions, social services, and infrastructure improvements and maintenance.[17,18,19] Such austerity measures, intensified by the escalating intervention of the federally controlled Fiscal Management Board, influence Puerto Rico's ability to address the underlying causes of vulnerability and hinder its capacity to recover and adapt.[20]

## Observed and Projected Climate Change for the US Caribbean

The assessment of observed and projected climate-related trends provides information for evaluating climatic and environmental consequences of future climate changes, risks, and impacts. The following assessment builds on the most recent findings.[1,12,20,21,22,23,24,25]

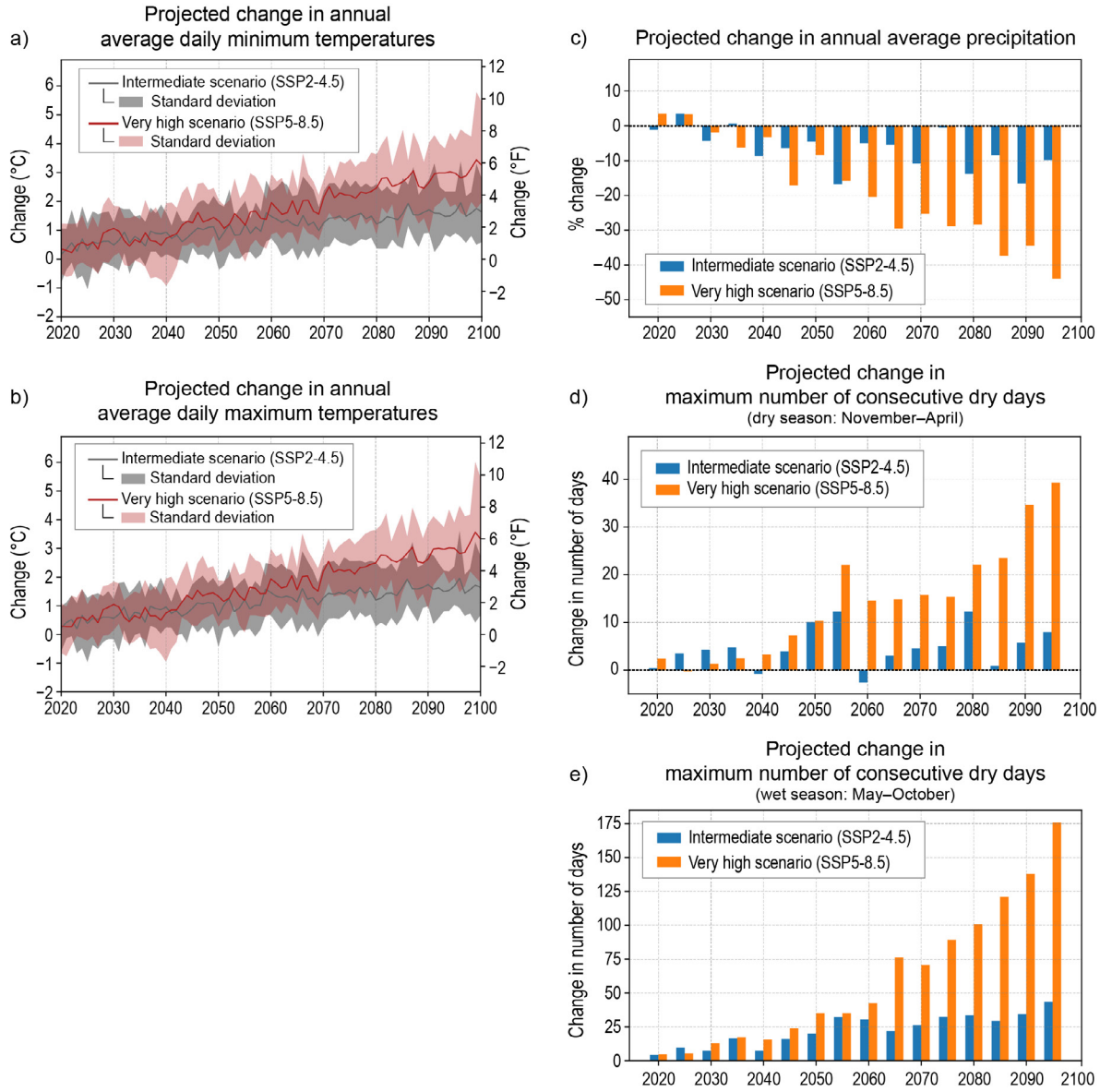
- Natural climate variability (Table 23.2), including the El Niño–Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Saharan dust events, has an important role in the subseasonal to interannual (year-to-year) climate within the US Caribbean.
- Daily average temperatures in PR have increased by 2°F since 1950. Minimum temperatures are increasing faster than daily average temperatures, with the largest increase for minimum temperatures at lower elevations. Projections for end-of-century temperatures show additional warming, from as low as 1.1°F under an intermediate scenario (SSP2-4.5) to as high as 7°F under a very high scenario (SSP5-8.5; Figure 23.2).
- No clear long-term trend is detected in seasonal or annual average rainfall over PR, although Figure 2.4 does show a small increase (less than 5%) in Puerto Rico in 2002–2021 compared to the 1901–1960 average. However, climate models project a significant reduction in annual average rainfall by end-century with reductions of 10% for SSP2-4.5 and 33% for SSP5-8.5. The rainfall reductions for SSP5-8.5 compared to SSP2-4.5 become increasingly larger after midcentury. The consequence of reductions in annual average rainfall is a large increase in the number of consecutive dry days, especially for the wet season (Figure 23.2).
- Within the Atlantic basin, the tropical cyclone rain rate is projected to increase by about 15% and the average storm wind intensity around 3% for a global average temperature increase of 3.6°F (2°C) above present-day levels. The number of intense tropical cyclones (Categories 4 and 5) are projected to increase as well (KM 2.2). There is some indication within Puerto Rico that tropical cyclone rainfall rates are increasing over the climatological record, increasing the likelihood of extreme events like Hurricane Maria's rainfall. Sea surface temperatures have warmed, and oceans are becoming more acidic, absorbing increased concentrations of atmospheric carbon dioxide ($CO_2$).
- Sea level is rising and is expected to continue to rise for centuries (KM 9.1). Long-range sea level scenarios indicate an additional rise of approximately 0.6 feet (0.2 m; Low scenario) to 1.4 feet (0.4 m; High scenario) by 2050 and 1.9 feet (0.4 m; Low scenario) to 6.8 feet (2.1 m; High scenario) by 2100;[25] for connections to Shared Socioeconomic Pathways [SSPs], see the Guide to the Report). The trajectory from tide-gauge observations from within the US Caribbean archipelago from 1970–2020 aligns with the Intermediate scenario out to 2050.

**Table 23.2. Large-Scale Circulation and Climate Variability**

Changes in the global (large-scale) circulation affect climate variability in the US Caribbean. El Niño–Southern Oscillation (ENSO) is the strongest source of year-to-year climate variability across the globe. An ENSO warm phase is referred to as El Niño and is associated with the warmer water in the eastern equatorial Pacific. The cool phase is referred to as La Niña and is associated with cooler water in that region. These warmer and cooler waters affect the atmosphere and worldwide weather patterns. The different phases of ENSO typically last between 6 and 18 months and recur every 2 to 7 years.[26,27,28] The North Atlantic Oscillation (NAO) is an oscillation in the sea level pressure between the Icelandic Low and North Atlantic Subtropical High.[29,30,31,32] A positive NAO occurs when both the Icelandic low and the Azores high are stronger than average, which creates strong atmospheric pressure differences within the North Atlantic. A negative NAO is associated with a weak Icelandic low and Azores high and weakened pressure differences within the North Atlantic. Saharan dust (consisting of particles containing minerals, organic matter, marine salts, viruses and bacteria, quartz, calcite, hematite, sulfates, and other materials) reaches the Americas from Africa (mainly from the Sahara and the Sahel). Dust season in the Caribbean occurs between May and September (summer), with maximum peaks from June to August.[31,32]

| Climate Variability | El Niño | La Niña | North Atlantic Oscillation (positive) | North Atlantic Oscillation (negative) | Saharan Dust |
|---|---|---|---|---|---|
| **North Atlantic Tropical Cyclone Activity** | Suppress activity | Increase activity | Suppress activity | Increase activity | Suppress activity |
| **US Caribbean Rainfall** | Weak to negligible impact | Weak to negligible impact | Suppress rainfall | Increase rainfall | Suppress rainfall |

## Temperature and Rainfall in Puerto Rico




**Puerto Rico is projected to become warmer and drier, with increasing uncertainty in the magnitude of change beyond midcentury; just how warm and dry depends on the scenario followed.**

**Figure 23.2.** Projected temperature and precipitation changes for Puerto Rico are shown for an intermediate scenario (SSP2-4.5) and a very high scenario (SSP5-8.5) to demonstrate the range of plausible future changes in the climate. Climate change projections are shown for annual average daily minimum (**a**) and maximum (**b**) temperatures, annual average precipitation (**c**), and maximum number of consecutive dry days during the dry season (**d**) and wet season (**e**). Both scenarios indicate a warmer and drier climate for Puerto Rico, but the magnitude of change for the very high scenario is alarming, especially when considering the availability of fresh water. The average maximum temperature increases for the end of the century (2071–2100) range from 2.8°F (1.5° C) for the intermediate scenario to 4.8°F (2.7° C) for the very high scenario. The increased temperatures, coupled with reductions in annual average precipitation at the end of the century of approximately 10% (intermediate scenario) to greater than 30% (very high scenario), are both indications of a significantly drier climate, with very large impacts anticipated for the very high scenario. A particular concern is the precipitation reduction during the wet season and the large increase in the number of consecutive days without rain, exceeding an increase of 115 days, on average, by the end of the century for the very high scenario. The bar plots in panels (c–e) are averages over five-year periods. All plots are differences relative to the entire period (2021–2100). Figure credit: NOAA NCEI and CISESS NC.

## Box 23.2. Missing Data in the US Caribbean and the Pacific Islands

The US Caribbean and Pacific Islands continue to face similar challenges related to climate change (Ch. 30), including geographic constraints (e.g., limited land area, variable topography), reliance on imports, critical dependence on local natural resources (fresh water, fisheries), and differential vulnerabilities to drought, sea level rise, and natural disasters. These territories are home to underserved and underrepresented communities that are systemically excluded from data collection efforts due to administrative structures that are rooted in colonialism.[33,34] These structures, combined with the lack of data, have resulted in capacity issues that continue to promote discrimination, inequity, and inequality in a wide range of sectors (e.g., health, natural resources, education, agriculture, food security, imports, and housing).[35,36,37,38]

Data for the US Caribbean are missing for metrics such as carbon dioxide sources and carbon sinks, municipality-level population projections, and locally relevant downscaled projections for both the changes in average conditions (e.g., temperature, precipitation) and extreme events (e.g., heatwaves, hurricanes, droughts, marine heatwaves, winter storms, dust storms). Even in cases where downscaled data are available for the US Caribbean region, they are not at a fine-enough resolution to distinguish small islands such as the US Virgin Islands, Culebra, and Vieques. Furthermore, Caribbean Traditional Knowledge systems and stewardship have been foundational in responding to climate change, but generations of knowledge have been undervalued, suppressed, and ignored by Western science and have only recently been recognized as valid knowledge sources at the federal level.[39,40] By identifying and addressing the underlying causes for missing information in the US Caribbean, scientific institutions will be able to more equitably develop future research and climate assessments. Doing so would better serve evidence-based decision-making throughout the Caribbean region.

## Key Message 23.1

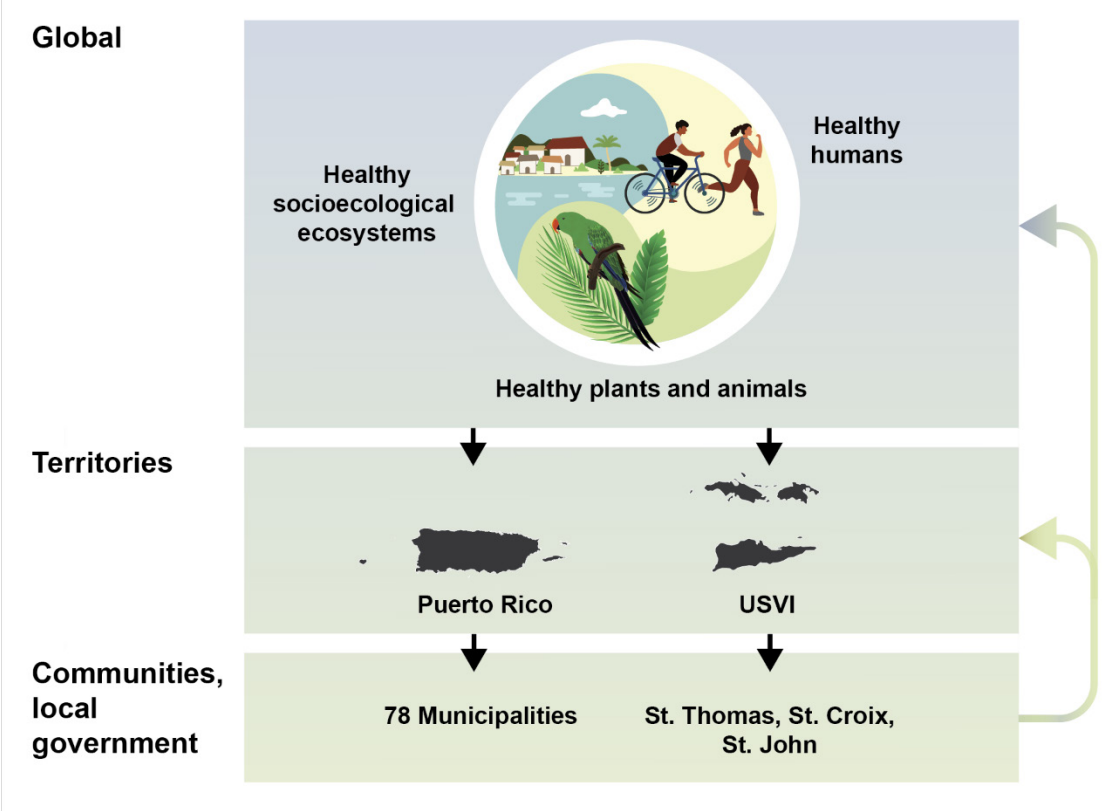
## Climate-Driven Extreme Events Exacerbate Inequities and Impact Human Health and Well-Being

Traditionally underserved and disadvantaged communities suffer disproportionate impacts from climate change because they have been systematically excluded from social services, secure livelihoods, quality education, and other social benefits that help sustain health and well-being (*high confidence*). Hurricanes and other climate-related extreme events have been associated with higher rates of disease, mental illness, and overall mortality, as well as loss of cultural heritage that is central to community identity (*high confidence*). As extreme weather events become more intense and more frequent, residents will continue experiencing increasing levels of noncommunicable diseases, excess mortality, behavioral health challenges, and loss of quality of life (*high confidence*). The frequency of heat episodes and the severity of hurricanes are both expected to increase in the region due to human-induced climate change, which will affect public health unless adaptation measures are taken (*high confidence*).

Long histories of colonization and systemic inequality shape the ability of the US Caribbean peoples to maintain health, quality of life, and overall individual and social well-being. Evidence from both PR and the USVI suggests risks from climate impacts to multiple elements of human health, including vector-borne and noncommunicable diseases, mental health, and overall quality of life (Ch. 15).[41] US Caribbean societies, with their multiethnic and multiracial makeup of high proportions of people of African and Indigenous descent, are more vulnerable to climate-related risks due to economic policies and social systems, varying levels of educational attainment, unemployment, poverty, out-migration, older-age demographics, food insecurity, colonialism, and unjust historical treatment.[42] As an effort to address these circumstances and the threat of more frequent extreme events, the One Health approach, similar to the community health concept

described in Chapter 15, mobilizes collaborative work among communities, stakeholders, practitioners, sectors, and disciplines to tackle climate change while improving well-being and quality of life for all living organisms (Figure 23.3).

### The One Health Approach




**In the face of climate change, the health of Caribbean people, plants, animals, and ecosystems depends on coordination across multiple scales and boundaries.**

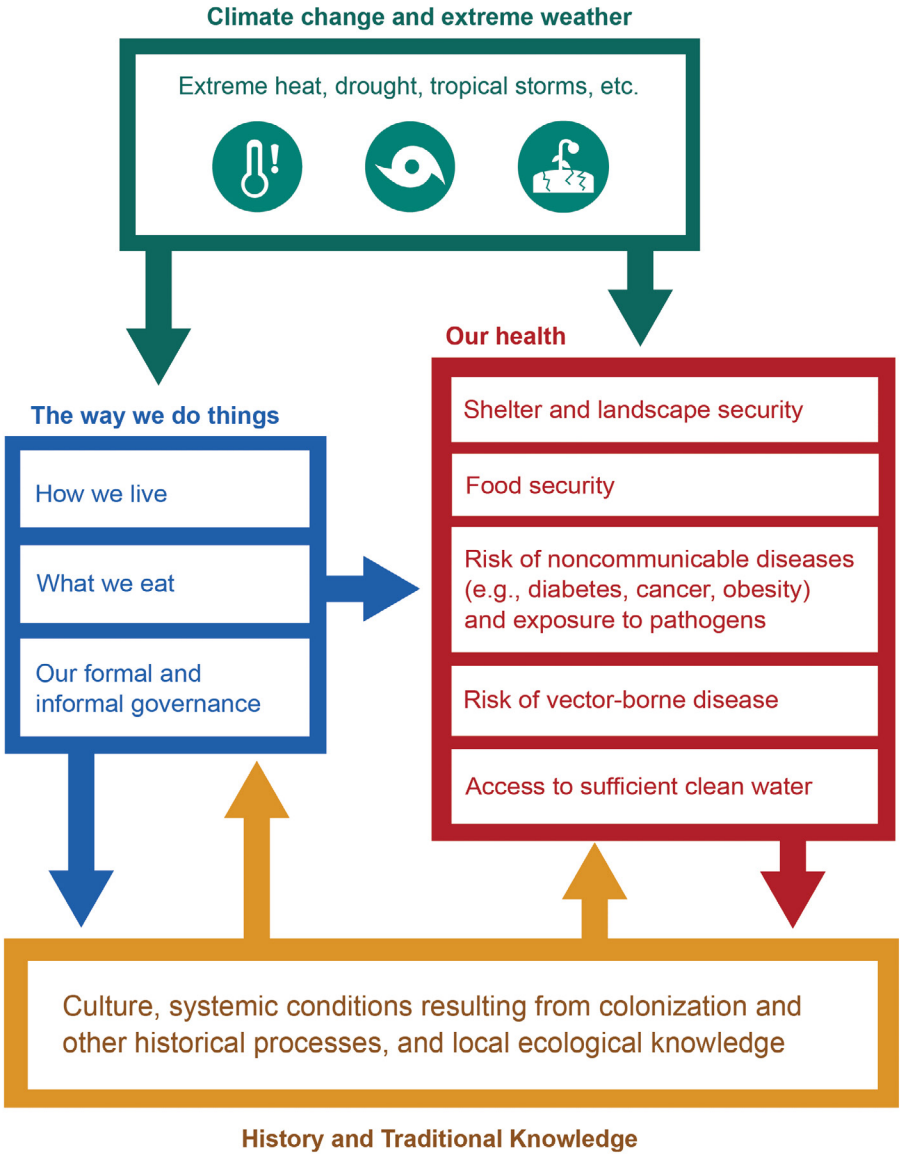
**Figure 23.3.** In the US Caribbean, climate change is interacting with the institutional and environmental context of the islands and the social determinants of health. Extreme weather events (e.g., powerful hurricanes, extreme heat, and droughts) are threatening access to clean air, safe drinking water, nutritious food, and safe settlements, as well as damaging infrastructure, reducing tourism, displacing vulnerable communities, promoting migration among islanders, disrupting ecosystem services, and endangering animals. The One Health approach illustrated here promotes collaborative work at local, regional, and global levels to achieve health for humans, ecosystems, and animals alike. Adapted from World Health Organization 2021[43] [CC BY-NC-SA 3.0 IGO].

## *Community Identity and Heritage Are Necessary for Resilience and Post-disaster Recovery*

US Caribbean cultural heritage is under threat due to changing climate conditions (Figure 23.4). Cultural heritage includes tangible elements (such as buildings, artifacts, monuments, and archaeological sites on land and underwater) and intangible elements (such as practices, ideas, representations, knowledge, music, songs, and ceremonies) that are recognizable components of community identity.[15,44] Research from recent hurricane events suggests that the magnitude of loss of heritage is severely underestimated[45,46] and that measures to mitigate climate impacts greatly threaten the preservation of cultural heritage and identity. For example, the traditional ways of life in the US Caribbean placed communities next to riverbanks for thousands of years. Archaeological sites associated with such communities, however, are under threat

from flood-control projects,[15] which entail channelizing, dredging, or covering rivers (e.g., USACE 2022[47]). These flood-control projects not only impact archaeological sites but also transform landscapes that are integral to the identity, recreation, and overall well-being of local residents.[15,48] Climate impacts also increase out-migration, which can lead to disintegration of traditional communities and loss of Indigenous and Traditional Knowledge (KM 30.2).[49]

## Climate Change and Public Health




**Public health is shaped by sociocultural factors and further affected by climate change.**

**Figure 23.4.** The impacts of climate change on human health in the US Caribbean must be considered in the context of the social, cultural, and historical realities of the islands. Shelter and food security, access to clean water, and communicable and noncommunicable diseases are certainly affected by climate, but they are also conditioned by culture, tradition, and historical and colonization processes. Figure credit: University of California, San Diego; University of the Virgin Islands; NOAA NCEI; and CISESS NC.

## Impacts of Extreme Events on Health and Essential Services

Extreme events, combined with deteriorating infrastructure and unequal distribution of social determinants of health, are expected to continue to cause interruptions in and insufficient access to healthcare services, as documented after Hurricanes Irma and Maria (KM. 15.2).[14,50,51,52] PR and the USVI have contaminated sites where hazardous waste has been discarded and, in some cases, improperly managed. Some of these sites—26 in PR and 2 in the USVI—are designated as EPA Superfund sites.[53] Extreme flooding has the potential to impact Superfund sites, spreading large amounts of contaminants and carcinogens into the surrounding environment.[54]

In the aftermath of Hurricane Maria, many older adults in PR experienced unmet needs that contributed to declining physical and emotional health, inadequate management of noncommunicable disease (NCD), social isolation, financial strain, environmental health issues, and excess mortality.[14,55,56] High levels of post-traumatic stress disorder (PTSD), depressive symptoms, and disaster-related stressors were also evident (KM 30.2).[42,57] Many hospitals suffered significant damages in both territories.[58] Various healthcare services were greatly affected, including vaccinations, cervical cancer screenings, surgeries, oncologic treatments, and dialysis.[59,60,61,62,63,64] Experts recommend that further disease-specific planning be delineated within the emergency response of each jurisdiction and in collaboration with disease-specific plans for relevant organizations.[65] For instance, region-specific and federal health plans, such as the CDC's comprehensive cancer control plans, would mitigate the impact of extreme weather on specific populations and maintain adequate cancer prevention and treatment care during and after disasters.

## Noncommunicable Diseases

The US Caribbean territories have high rates of NCDs, as well as increasing rates of impaired mental health.[42,66] After Hurricane Maria, there were obstacles to providing nutritious, affordable, and culturally acceptable food appropriate for people with NCDs.[42] In PR and the USVI, 67.5% and 65.2% of the population, respectively, are overweight, and 31.4% and 32.5% live with obesity;[67] these conditions are considered predictors of early mortality.[68] Surveys in PR in 2017 and 2019, pre- and post-Hurricane Maria, show an increase over that time span in the prevalence of NCDs and depression in adults.[69] In March 2018, an online survey identified PTSD in 44% of respondents in PR and 66% of those displaced from PR to Florida.[70,71]

## Climate-Driven Vector-Borne Diseases

Vector-borne diseases (VBD) in the Caribbean, such as dengue, Zika, and chikungunya, are mostly transmitted by the *Aedes aegypti*, *Aedes albopictus*, and *Culex* mosquitoes (KM 15.1). The abundance of *Ae. aegypti* and *Ae. albopictus* are influenced by temperature and precipitation, and both species have excellent adaptation skills under extreme temperature and precipitation conditions.[72,73,74,75,76] Factors in the US Caribbean that favor VBD outbreaks include climate change, inequality, poverty, serotype profile (virus variation), immunity, deficient water and waste management, and lack of community awareness.[75]

## Climate Impacts on Human Zoonotic Diseases

Human leptospirosis is an important zoonotic disease—that is, a disease that transmits from animals to humans—with worldwide distribution. It was first reported in PR in 1942, while the first cases of leptospirosis in the USVI were reported in the aftermaths of Hurricanes Irma and Maria. Recent evidence suggests an excess risk in PR of leptospirosis associated with flood-prone areas, heavy rainfall, and higher temperatures.[77] Extreme weather events such as tropical storms, heavy rainfall, and floods are expected to result in an upsurge in the number and magnitude of leptospirosis outbreaks.[78] Under the above-mentioned climate scenarios, outbreaks in both US territories are *very likely* to occur following extreme weather events.

## Excessive Heat and Differential Social Burden of Climate Impacts

Heatwaves are increasing the risk for heat-related illness and death (KMs 6.2, 15.1; Figure 15.1). Conditions of extreme heat in the Caribbean have intensified since 1980. Recent research suggests an increasing trend in the number of days with heat stress (days above 39.9°C [103.8°F]) for the Caribbean region since 1980.[79] Several factors contribute to heat vulnerability and sensitivity, including:

- Populations at the extremities of age (e.g., newborns, children, elders)
- Pregnant women/people
- Individuals who are
  - living in single-person households
  - living below the poverty line
  - working in confined spaces with poor ventilation
  - working outdoors and exposed to risk factors such as direct sunlight or high humidity combined with extremely high air temperature
  - living with disabilities
  - living with chronic health conditions (e.g., obesity, hypertension, diabetes, cardiovascular disease, respiratory illness)
  - without health insurance coverage

With rapid urbanization in the USVI and PR and past population growth, urban heat island effects have become stronger (KM 12.2). San Juan, PR, is already showing evidence of these effects;[80] extreme heat episodes there have been associated with a significant increase in mortality and an increased relative risk for stroke and cardiovascular diseases.[81] Cooling indoor environments help lessen the impact of heatwaves, but energy demands on a crumbling power infrastructure, as well as rising costs of living, create climate risks associated with inequality, as only a section of the society will be able to afford cooling equipment.[82]

## Human Health and Natural Sources of Air Pollution

Recent studies suggest that global warming will make dust storms more severe in the Mediterranean and the Atlantic (KM 14.1).[83] In the US Caribbean, dust particles carried across the Atlantic from the Sahara, mostly during summer, affect climate, weather, and ecosystems, including coral reefs, forests, and human populations.[84,85,86,87,88,89,90,91,92] Saharan dust provides nutrients to terrestrial and marine ecosystems. However, in PR, Saharan dust has been associated with increased cardiovascular and respiratory risks;[93] it has also been linked to increased risk of emergency room visits and hospitalizations related to asthma in children in Trinidad and Tobago,[94] Guadeloupe,[95] and Grenada.[96] As humidity and temperatures rise, the abundance of mold and spores in the air also impacts air quality and thus respiratory NCDs.

## Sargassum and Health Intersections

Sargassum is a brown seaweed that floats in the Atlantic Ocean and provides an important habitat for migratory organisms that have adapted specifically to it. These algal mats are sometimes pushed by wind and currents into the Caribbean Sea and are frequently reaching the coasts of the region's islands. Evidence suggests that these events threaten coastal ecosystems and social and cultural activities (e.g., fisheries), with negative economic impacts (e.g., reduced tourism and degraded infrastructure; Ch.10; KM 1.2) and adverse human health effects (e.g., heart palpitations, shortness of breath, and skin rashes) due to hydrogen sulfide from decomposing sargassum in the air and direct exposure to algae.[97,98,99,100,101,102,103] While sargassum mats can be harvested for beneficial uses such as fertilizer and animal feed and as an energy source, its use as a fertilizer could transfer heavy metals to crops.[104,105,106] While the impact of this phenomenon has not yet been assessed for the US Caribbean, these conditions are expected to worsen as climate change intensifies.

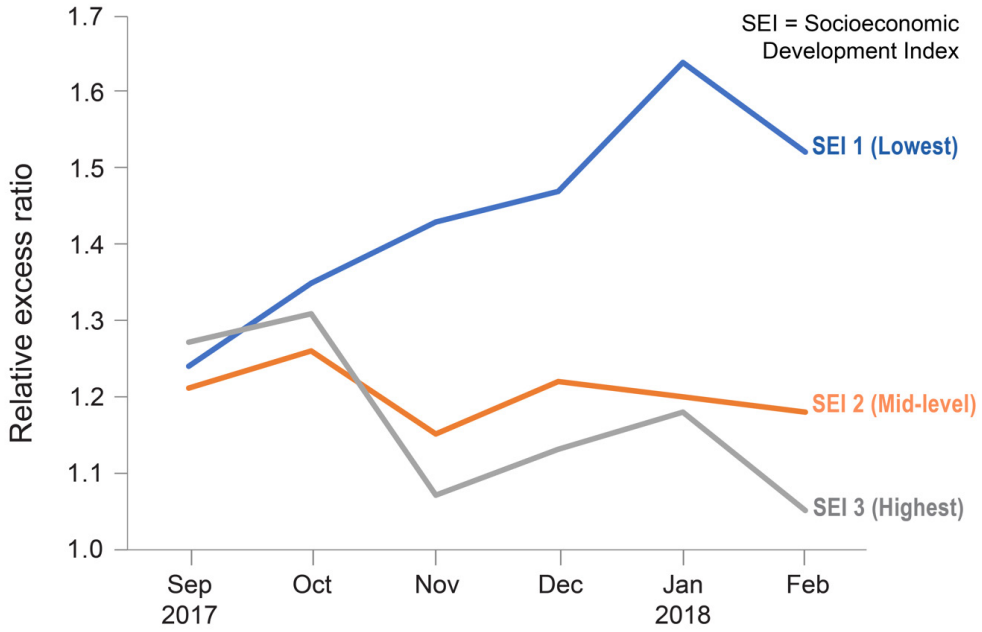
## Water Resources and Human Health Interactions

Factors related to environmental health and changing climate (e.g., sea level rise, saltwater intrusion, and pollution) impact water security. Inefficient water management and climate change, including the increasing intensity of storms, have led to growing concerns about water scarcity and water insecurity for both territories.[107] While Traditional Knowledge has been shown to mitigate water scarcity during emergencies—such as individuals and communities activating historic or abandoned water sources during recent disasters[44,108]—these responses might not be enough, as Traditional Knowledge is also threatened, cultural heritage is being lost, and the magnitude of impacts exceeds previous experience (KM 30.1). Older traditional farmers in Puerto Rico have recorded a reduction in freshwater availability in streams and springs that impacts their traditional access to fresh water and their food production, which they consider a heightened risk for their health.[15] Reports on communities in both PR and the USVI that are systematically excluded from welfare, education, and other social services and benefits link inequity to poverty levels and the impact of status on the development and interpretation of laws and programs that address these issues (KM 15.2). Studies after hurricanes in PR and the USVI have shown water pollution, disease vectors, and bacteria in the drinking water supply, all of which are expected to worsen with expected impacts of climate change, thus affecting livelihood security.[109,110,111]

## Underestimation of Mortality

Total excess mortality identifies how many more observed deaths happen after a specific event in comparison to the baseline historical trend of expected deaths had the natural event not occurred. After Hurricane Maria in PR, a large excess mortality was noticed by many people but not identified by the official certification of 64 deaths. Six months after Maria, a commissioned independent study identified 21% more deaths in males than expected and a total excess mortality estimate of 2,975 (Figure 23.5),[56] including both direct (related to hurricane injuries) and indirect (related to lack of access to effective care after the storm) deaths. These deaths mostly affected the most vulnerable populations, including those at lower socioeconomic levels.[56] The distribution of causes of excess mortality is predominantly driven by chronic noncommunicable diseases.[112] Further analysis estimated 514 excess deaths in the Puerto Rican population displaced to the US mainland.[113] Evidence shows that considering only direct hurricane injuries greatly underestimates the overall impact on excess mortality. After Hurricane Fiona in 2022, the mortality in Puerto Rico was 1.15 times higher in adults older than 75 years of age, who experienced 226 excess deaths.[114]

### Excess Mortality from Hurricane Maria in Puerto Rico




**Excess mortality from Hurricane Maria was most common among Puerto Rico's most impoverished residents.**

**Figure 23.5.** Between September 2017 and February 2018, 2,975 excess deaths—that is, above what the mortality rate would have been if the storm had not occurred—were estimated in Puerto Rico due to Hurricane Maria. Mortality was higher for individuals living in low-income municipalities, for those with the lowest scores on the Municipal Socioeconomic Development Index (SEI)—a multidimensional index of poverty developed by the Government of Puerto Rico—and for men aged 65 years or older. These results are useful to health officers, emergency preparedness personnel, and residents, as they help to prepare for and to mitigate the potential effects of hurricanes. Adapted from Santos-Burgoa et al. 2018.[115]

## Key Message 23.2

## Ecology and Biodiversity Are Unique and Vulnerable

Coastal and terrestrial ecosystems provide a large number of goods and services that are vital to the islands' economies and to the health and well-being of their residents (*high confidence*). These essential systems are degraded by human actions and climate change, thereby reducing the benefits they provide to people, as well as their functionality as habitats for protecting biological diversity (*high confidence*). Climate change is expected to exacerbate the degradation of ecosystems (*very likely*, *high confidence*). The success of climate adaptation strategies will depend on reducing all sources of stress on ecological systems (*medium confidence*).

PR and the USVI are home to diverse aquatic and terrestrial ecosystems and are rich in natural resources and cultural heritage. Residents depend on the region's natural resources and ecosystem services for their well-being and livelihoods. These important ecosystems are being degraded by economic activity, habitat destruction, land conversion, pollution impacts, and overfishing.[116] Climate change impacts on land will have environmental consequences along the coast and beyond. Impacts and consequences will vary by territory, species, and ecosystem type.

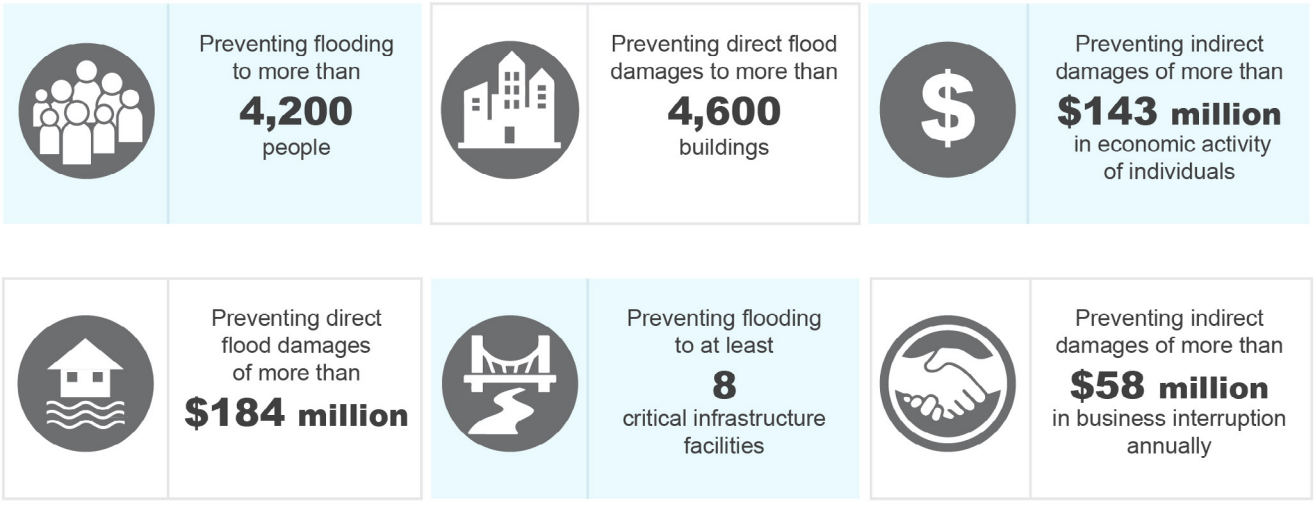
## *Impacts of a Changing Climate on Ecosystem and Biodiversity Goods and Services*

Climate stressors (e.g., extreme precipitation, droughts, frequent and intense tropical cyclones, and steady increases in surface temperatures) and non-climate stressors (e.g., pollution and deforestation) interact to impact ecosystems and the services they provide to people (Ch. 9). Ecosystem services include provisioning services such as food, feed, and fiber; regulating services such as climate regulation, flood control, and air and water purification; cultural services such as recreation and spiritual and aesthetic benefits; and supporting services such as nutrient cycling, primary production, and soil formation.[117] Climate change is increasingly compromising ecosystem goods and services (Ch. 8).

Coastal zones—often highly valued and the focal point for cultural activities, Traditional Knowledge, tourism, and industries essential for economic and social vitality—are at risk from climate change (KM 9.2).[118,119,120] The US Caribbean coastline is roughly 876 miles (1,410 km) in length (PR, 700 miles [1,127 km]; USVI, 175 miles [282 km])[121] and is composed of nested coastal ecosystems such as sandy dunes, beaches, mangroves, salt flats, coral reefs, and seagrass beds. The high population density, concentrated development, and critical infrastructure located within 0.6 miles (1 km) of the coastline are highly vulnerable to coastal hazards and climate stressors.[20] The combined destructive power of wave action and intense rainfall from Hurricanes Irma and Maria alone damaged over 12% of coral reefs,[122,123,124] caused beach loss of 1.2–3.1 miles (2–5 km),[119,125,126] eroded dunes,[118,127] and devastated almost 33% of mangroves.[128] These impacts added to the degradation of ecosystems caused by other climate stressors (KM 8.2).

The loss of recreational benefits from the degradation of coastal reefs is expected to reach $172 billion (in 2022 dollars) by 2100 under a very high scenario (RCP8.5).[129,130,131] In 2019, an assessment quantified the annual coastal flood risk-reduction benefits provided by all US coral reefs, including those in PR and the USVI, as illustrated in Figure 23.6.

### Annual Expected Benefits from Coral Reefs in the US Caribbean




**Coral reefs provide substantial coastal protection benefits to the US Caribbean each year.**

**Figure 23.6.** Coral reefs are a major component for recreational and commercial fisheries, coastal protection, and the tourism economy. Acting as a natural defense, coral reefs dissipate incident wave energy and protect coasts from erosion and flooding. Arguably, they are one of the most economically valuable ecosystems.[130] Economic estimates are in 2010 dollars. Figure credit: Caribbean Coastal Ocean Observing System.

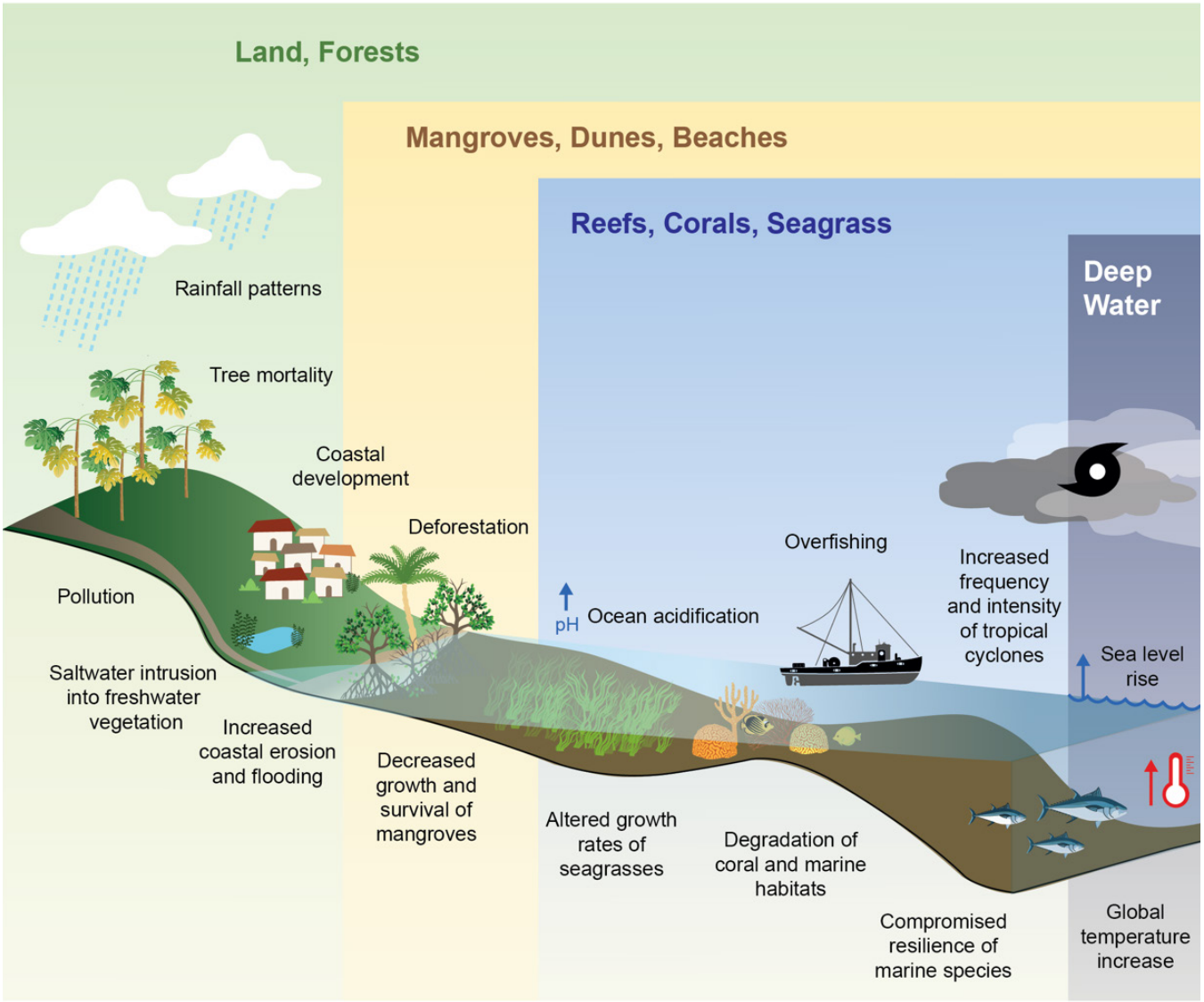
Sediment and contaminant runoff derived from various land-based activities also threaten coastal ecosystems.[125,132] Runoff of land-derived sediment could directly impact coral regeneration capacity, growth, and mortality, as well as the ecosystem services they provide.[93] Cross-jurisdictional strategies and ecosystem-based management principles must be adopted to significantly reduce the adverse impacts of anthropogenic/land-derived pressures on coastal ecosystems.[133] In PR's Guánica Bay watershed, for example, a watershed management plan is being implemented to restore the health of coral reefs damaged by sediment and nutrient runoff.[134]

Caribbean forests are highly diverse, ranging from coastal mangroves to dry forests. These ecosystems provide many services, including habitat, recreation, coastal protection, and improved air and water quality.[135] Although forests are adapted to withstand frequent natural disturbances, projected changes in temperature and rainfall are expected to impact the amount of fruiting and flowering, tree productivity, and nutrient cycling, as well as increase the likelihood of tree mortality, among other impacts (KM 7.2). Furthermore, they can alter the forest ecosystem's biogeochemical processes and affect their composition, structure, and functioning.[136] For example, trees within northeastern PR are already operating above their optimum temperature for photosynthesis; thus, increasing temperatures (which are projected) will lead to the release of more carbon dioxide (a major driver of climate change) into the atmosphere.[137,138,139] Meanwhile, research on tropical forestry, ecology, and conservation in the Luquillo Mountains in PR has reversed the paradigm that tropical ecosystems are fragile, demonstrating instead that they exhibit remarkable resilience to many forms of disturbance.[140]

## *Emerging Issues and Future Directions*

Ecosystems that are already degraded or stressed may have lower adaptive capacity and resilience. Increased stress from climate change may drive ecosystems to tipping points,[141] with potentially irreversible socioeconomic consequences for coastal socioecological systems and community livelihoods.[141] Maintaining, enhancing, and/or restoring ecological connectivity and corridors as conservation strategies are key to helping ecosystems adapt to climate change (Figure 23.7; Ch.1; KM 3.6).

## Ecosystem Stressors




**Both climate and non-climate stressors affect aquatic and terrestrial ecosystems and biodiversity in the US Caribbean.**

**Figure 23.7.** The cumulative effects of these stressors could result in the degradation of aquatic habitats, increases in coastal erosion and flooding, tree mortality, alterations in the growth of mangroves and seagrasses, and diminishment of resilience and adaptive capacity. Adapted with permission from Fitzpatrick and Giovas 2021.[142]

## Key Message 23.3

## Climate Change Threatens Water and Food Security

US Caribbean food and water systems are becoming increasingly vulnerable to the escalation of climate change, including stronger hurricanes, more severe drought, warmer air temperatures, and other extreme weather (*likely*, *high confidence*). Because the territories are heavily reliant on imported foods, they are affected by climate changes occurring both within and outside of the region (*high confidence*). Reductions in average annual rainfall, increasing air temperatures, and rising sea levels will adversely affect freshwater availability in the future (*medium confidence*). Improved adaptation efforts would benefit from a better understanding of the ways food and water systems interrelate and of the cascading impacts generated by climate change (*medium confidence*).

Food and water security are important for well-being and emerge from complex social and environmental interactions across groups and regions in the Caribbean. About one-third of Puerto Rican adult residents in 2015 lacked consistent access to adequate food, higher than the rate on the US mainland (12%).[143,144,145] Low-income households were more than three times as likely to experience food insecurity as households with higher income.[145] These numbers are influenced by lower governmental expenditures for key economic security programs relative to other US states or territories.[146]

Within this context, climate change can deepen food and water insecurity in the region.

### Characteristics of the Island Food Systems

More than 80% of the food consumed in PR comes from the US mainland[147,148,149] on US-flagged ships, as required by law.[150] Most of the food imported by PR arrives at a single port of entry and is transported by only a few maritime companies.[151] In PR, food imports have been increasing since the 1950s.[151,152]

The agricultural sector represents an important source of employment and food security, although production accounts for less than 1% of the GDP in Puerto Rico.[153] Between 2012 and 2018, the total number of Puerto Rican farms declined by 37%, with farms less than 10 acres in size declining by about 57%.[154] The main classes of production are plantains and bananas, coffee, root crops and tubers, fruits and vegetables, nursery crops, and grasses.[154] Cattle and dairy production generate more than 25,000 jobs on the island and occupy more than 50,000 acres.[155,156]

The USVI imports more than 90% of its food, with importation of most food categories increasing over time.[157,158] The main crops grown and sold on the islands are vegetables, nursery crops, and tree crops. Between 2007 and 2018, the sale of these main crops increased by 1.1%, but they still represent less than 1% of GDP.[159,160]

### Characteristics of the Island Water Systems

In PR, approximately 82% of water used is derived from surface water sources (reservoirs and streams), with the remaining 18% extracted from groundwater sources.[161] The total storage capacity in reservoirs is decreasing due to sedimentation.[162] Rain harvesting and desalination plants are also sources of potable water, primarily in the USVI. There is a tension between water for consumption and agricultural uses. PR has four irrigation districts around the main island that draw on a network of reservoirs to provide water to farmers for crops via irrigation canals. The Puerto Rico Aqueduct and Sewer Authority (PRASA) also purchases rights to the water in the districts. Water from PRASA is expensive and cannot be used for

agriculture.[149] Due to faulty infrastructure, mismanagement, evaporation, and theft, approximately 50% of water purchased by PRASA from the irrigation districts is lost before reaching the public.

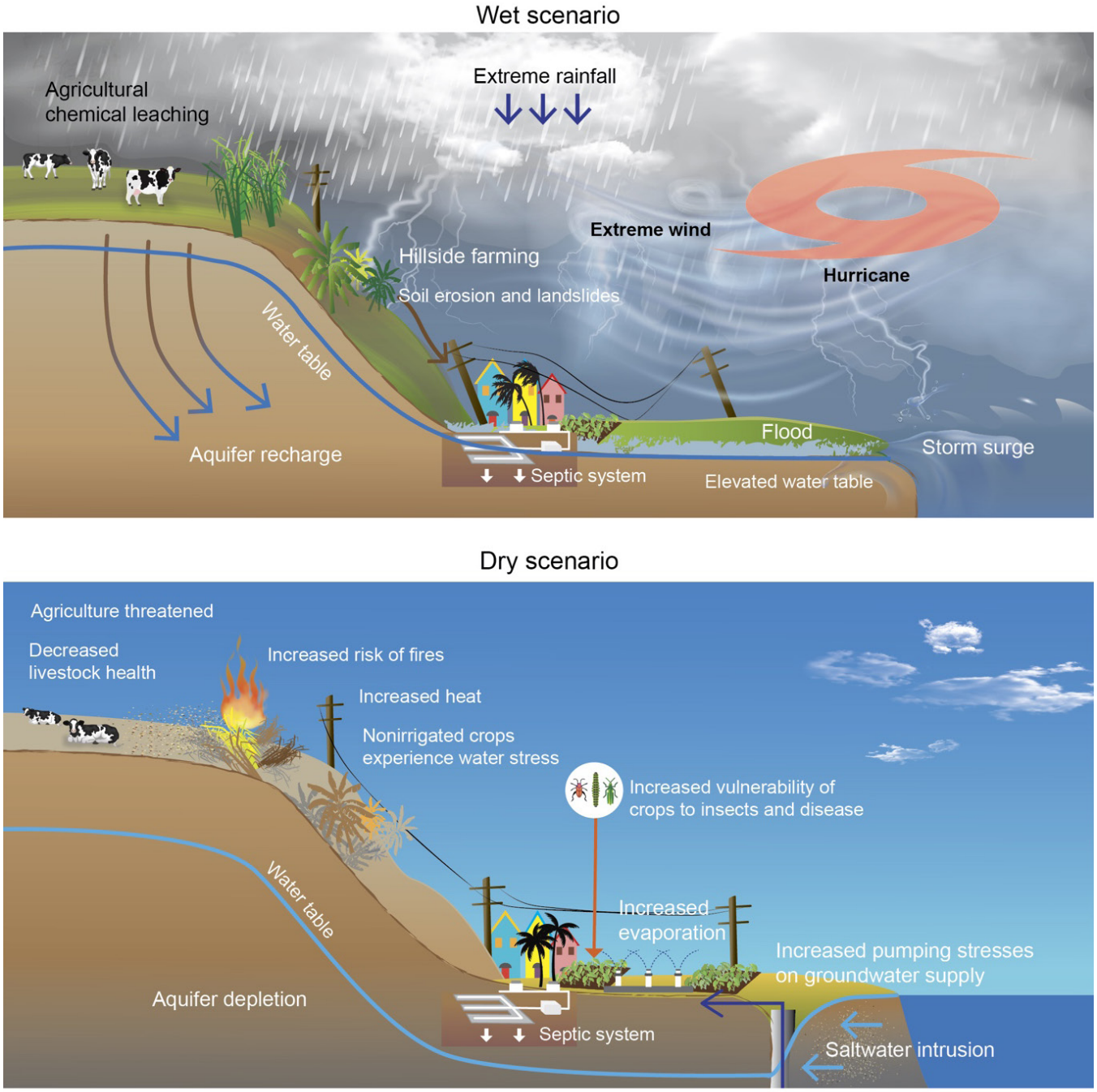
Outside of these four irrigation districts, surface runoff is stored in ponds or pumped from aquifers. The South Coast aquifer (SCA) has declining water levels due to over-pumping, which in some cases has lowered the water levels below sea level, leading to salinification.[163,164,165] The cost of water to farmers is low,[149] which may discourage them from using water efficiently. Irrigation scheduling can be used to optimize irrigation water use;[166] however, limited data exist on the irrigation scheduling methods used by farmers in PR and the USVI. About 10%–20% of the water introduced into the irrigation canals is lost by leakage.[161]

In the USVI, farmers access water from surface ponds and aquifers and from stored rainwater in cisterns. On St. Thomas, the majority of the farming occurs in the drier Estate Bordeaux.[167] Farmers there depend mostly on private and public cisterns and ponds or on wells that are privately managed. On St. Croix, most farmers depend on groundwater from deep wells or water from private cisterns or ponds they own or that are managed by the USVI Department of Agriculture. On St. John, farmers capture water in privately owned ponds. Few farmers depend on the public water system.

## *Climate Stressors on Food and Water System Components*

Climate change is affecting and will continue to affect the region's food and water systems (Figures 23.8, 23.9).[147] In the past, strong winds and heavy rain have destroyed crops and caused livestock mortality. They have also led to landslides, soil erosion and degradation, flooding, and sediment contamination of water.[168] Between 1995 and 2017, agricultural losses attributed to hurricanes in PR accounted for 3%–26% of the total estimated economic damages. Hurricane Maria in 2017 alone caused more than $2.3 billion (in 2022 dollars) in losses and damages to crops and infrastructure,[169] which represented a reduction of about 80% of the main island's total agricultural value.[170] Beyond these direct impacts, a substantial portion of agricultural losses were caused by indirect effects of tropical cyclones, including energy outages, disrupted telecommunication and water supplies, and damaged roads and irrigation systems.[152,168,171] With a projected increase in the intensity of major tropical cyclones, these impacts are expected to worsen without investments to make food and water systems more resilient (KMs 8.3, 11.3, 30.1).

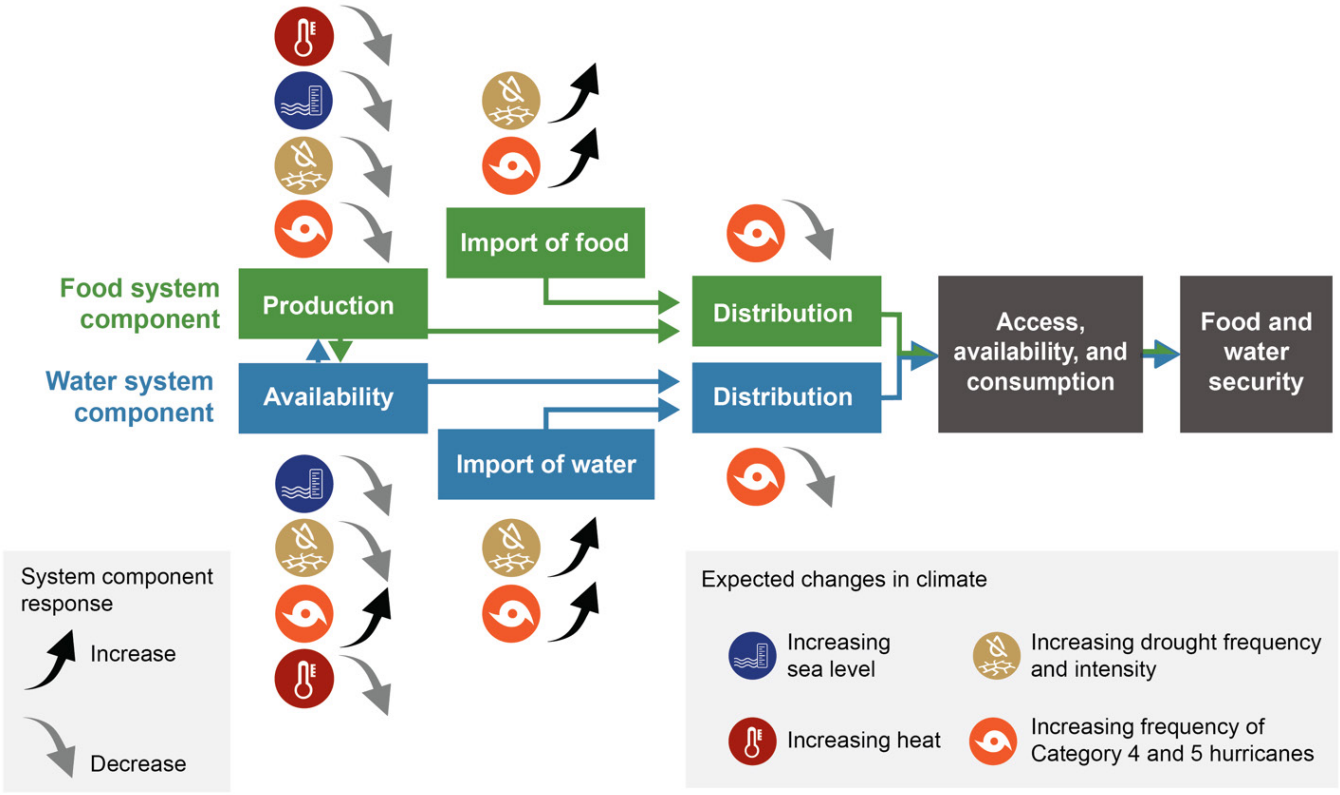
## Climate Impacts on Food and Water Systems from Ridge to Reef




**Risks to food and water systems differ under wet and dry scenarios.**

**Figure 23.8.** (**top**) In periods of wet conditions, saturated soils coupled with heavy rainfall from hurricanes and storms can lead to flooding and, in turn, soil erosion and vegetation and crop destruction. Strong winds and floods can also damage infrastructure needed for food and water distribution. Excessive rain combined with higher sea levels affects water quality through the leaching of agricultural chemicals and wastewater from septic systems. (**bottom**) Dry conditions, on the other hand, increase groundwater pumping for irrigation. When combined with sea level rise, these conditions can also lead to saltwater intrusion into coastal aquifers. Figure credit: University of Puerto Rico, North Carolina State University, USDA Forest Service, University of Arizona, and University of the Virgin Islands.

## Food and Water Systems




**Cascading impacts of climate change affect food and water systems and security.**

**Figure 23.9.** The figure displays the effects of the main climate changes that directly affect the islands on each of the system's components. The up and down arrows show the increasing or decreasing effect of a given climate change stressor on the food or water system components. For example, the increasing frequency of Category 4 and 5 hurricanes will cause a decrease in the distribution of food and water. The effects of climate changes are moderated by external influences such as socioeconomic changes that precondition the islands to be more or less susceptible to climate changes. Figure credit: University of Puerto Rico, USDA Forest Service, University of Arizona, North Carolina State University, and University of the Virgin Islands.

Drought has been common to PR and the USVI. Between 1950 and 2016, periods of severe drought occurred across the Caribbean (1974–77, 1997–98, 2009–10, and 2013–16). Regions of PR in 2020 and the USVI in 2021–2022 were declared by the USDA to be natural disaster areas because of drought conditions. The 2014–2016 drought was characterized as the most severe on record.[172] Livestock losses in 2015 accounted for about 62% of all reported economic losses, and plantain losses accounted for 22%. The combination of periodically dry conditions with a warming trend leads to aridification and compounding impacts (KM 4.1).[173] Aridification leads to increased demand for irrigation. Higher demand for irrigation, coupled with salinification of aquifers from sea level rise, suggests that groundwater aquifers like the SCA will be under increasing pressure in the future. Following 2015, the government of Puerto Rico created the Scientific Drought Committee. The USDA Caribbean Climate Hub created the Caribbean Drought Learning Network in 2021 to integrate drought-related information, initiatives, and programs in PR and the USVI.[174] These initiatives can help preparation and response to future droughts.

Increasing average and intermittent extreme temperatures are expected to reduce crop yields,[175] especially in tropical regions.[176] Expected impacts on crops include reduced seed yield,[177] reduced pollen production, and increased rate of senescence (i.e., shortening of a crop's life cycle).[178] The negative effects of increasing

temperature worsen under water deficit conditions.[178] Higher temperatures also increase the potential for wildfires;[179] can affect the range of weeds, diseases, and insects;[180] and can cause heat stress in farmworkers (KM 4.2).[181] Increased atmospheric $CO_2$ levels may counteract the negative impacts of higher temperatures; however, adequate water is required to take advantage of $CO_2$ fertilization.[182] Crop water use may increase[183,184,185] or decrease[186] under climate change conditions, depending on site-specific changes in the meteorological parameters.

Both drought and elevated temperature have negatively impacted livestock producers in PR and the USVI.[152,156] High temperatures lead to heat stress, which reduces animal productivity, increases the proliferation and survival of parasites and disease pathogens, reduces the ability of dairy cattle to produce milk and gain weight, and lowers conception rates. Furthermore, bovine breeds in PR and the USVI are more susceptible to heat because they were largely introduced from temperate regions, such as from within the US mainland.[155,156]

Soil health has direct effects on the ability to maintain agricultural production in the future and to adapt to climate change. Soil organic carbon is affected by increasing temperatures. Both mineralization and the loss of organic carbon and nitrogen increase under elevated temperatures.[187] Extreme variation in rainfall can promote carbon loss via soil drying and soil erosion. Certain conservation practices—such as no-till farming and the use of cover crops—can promote soil health and enable the sequestration of larger amounts of carbon in the soil.[187,188,189] The USDA Natural Resources Conservation Service is promoting methods to increase soil health in PR and the USVI.[190]

## Social Protection

Crop insurance plays an important role in reducing climate impacts. In PR, about 50% of farmers participate in the Puerto Rico Crop Insurance Corporation (PRCIC; a similar program is currently unavailable in the USVI). Between 2010 and 2019, the PRCIC paid compensation for agricultural losses for 25 events, all but one—a wildfire—related to rainfall (hurricanes, tropical storms, tropical depression floods, and extreme rains). Ninety-eight percent of the total insurance payouts for the 2010–2019 period was for losses caused by hurricanes. The insurance program, however, does not cover drought.[152]

## Emerging Issues

Areas receiving increased attention essential to managing extreme weather include plant and animal breeding,[156,191] crop production within controlled environments,[192] precision agriculture,[193] irrigation scheduling,[194,195] and flood and drought early warning systems.[196,197] Increased local food production and the need to balance water use among sectors will become increasingly important issues.[149] In the USVI, the lack of information to quantify economic losses associated with climate impacts, such as the effects of drought on food and agriculture, is also an issue. Superimposing climate change on top of other compounding issues (internal and external) will create additional stressors and have cascading impacts on food and water systems within the region. Understanding the complexity of the islands and their food and water systems will aid in the creation of contingency planning for problems that may arise.

## Key Message 23.4

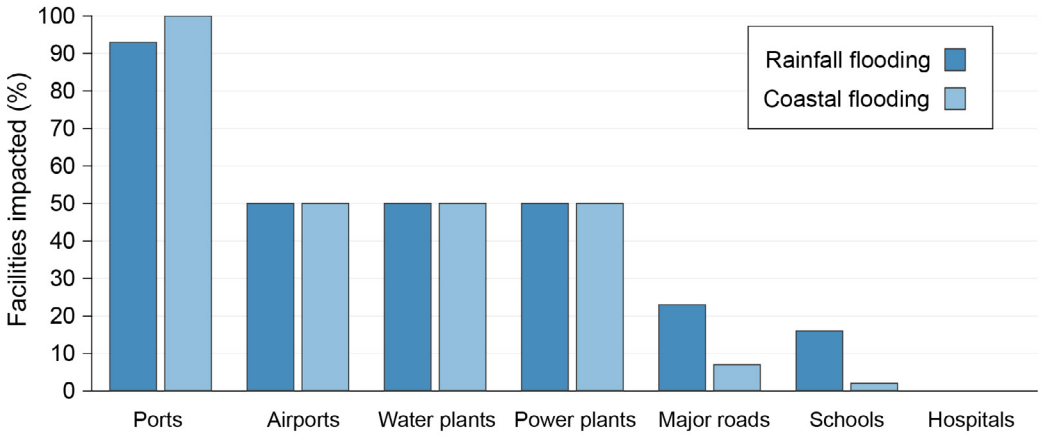
## Infrastructure and Energy Are Vulnerable, but Decentralization Could Improve Resilience

Climate change has created profound risks for the US Caribbean's critical infrastructure, already weakened from years of disinvestment and deferred maintenance (*high confidence*). Increasingly powerful storms, along with rising sea levels, are severely impairing infrastructure systems, with increasing damage projected in future years (*likely*, *high confidence*). Dependence on fossil fuel imports increases energy insecurity (*high confidence*). Infrastructure improvements, coupled with a new paradigm focused on decentralization, adoption of distributed solar, and shared governance, could help limit residents' vulnerability to health and other risks associated with loss of essential services (*likely*, *medium confidence*).

The 2017 and 2022 hurricane seasons in the Caribbean demonstrated the vulnerability of critical infrastructure (e.g., energy, water, healthcare, transportation, telecommunications, wastewater, stormwater, and solid waste) in Puerto Rico and the USVI to natural hazards.[23,24,198] This vulnerability is mainly caused by years of deferred maintenance, the recurrence of powerful tropical storms,[199,200] and a centralized mode of production and governance that limits redundancy, flexibility, and, therefore, the ability to anticipate and adapt to future scenarios that climate change will create.[201,202,203,204,205]

Powerful tropical storm impacts are exacerbated by higher sea levels, which increase storm surge and prevent proper drainage of higher stormwater volumes.[12,21,25,206,207,208,209] As a consequence, critical infrastructure systems, which tend to be concentrated near the coasts and floodplains, will experience compounded effects of different hazards and disrupt the movement of people, goods, and services (Figure 23.10; KM 9.2).[204,210] Climate change is also causing higher temperatures and drier conditions,[12,21,211] thereby reducing water availability, increasing water demand, and intensifying saltwater intrusion into aquifers.[212,213] And, because infrastructure systems are interconnected and interdependent, the disruption of any single system will affect the operation of other systems. Currently, even outside of droughts, water for human needs competes against demand for power production (KMs 4.2, 5.1).[214] Similarly, even without hurricanes, sea level rise affects the operation of marine, air, and surface transportation systems,[204] and stormwater flows overwhelm wastewater systems.[200,204]

## Infrastructure at Risk of Flooding in the US Virgin Islands




**Many types of facilities in the US Virgin Islands and Puerto Rico are threatened by storm-induced flooding.**

**Figure 23.10.** The figure shows the percentage of critical infrastructure currently located in flood zones (rainfall flooding caused by rainstorms and coastal flooding caused by storm surges and waves) in the US Virgin Islands. Many similar facilities are at risk in Puerto Rico,[215,216] but data are missing to represent the information in this report. Facilities at risk of flooding or that are flooded might not be able to provide critical services to communities when flooded, and there might not be another alternative available. The figure shows vulnerabilities under current climate conditions; additional flooding caused by sea level rise or potential future increases in intensity and duration of rainstorms is not included. Figure credit: University of the Virgin Islands, NOAA NCEI, and CISESS NC.

Increasing temperature and heatwaves will drive power and water demand, and wetter storms will increase demand on wastewater and stormwater pumps.[217,218] Damage from increased rainfall rates from hurricanes and increased hurricane intensities are projected to increase solid-waste flows, and response and recovery activities may intensify the use of single-use items such as utensils or water bottles.[24,219,220] Demand for healthcare is also expected to increase as communities experience higher temperatures or greater exposure to stormwater or wastewater and associated waterborne pathogens.[221]

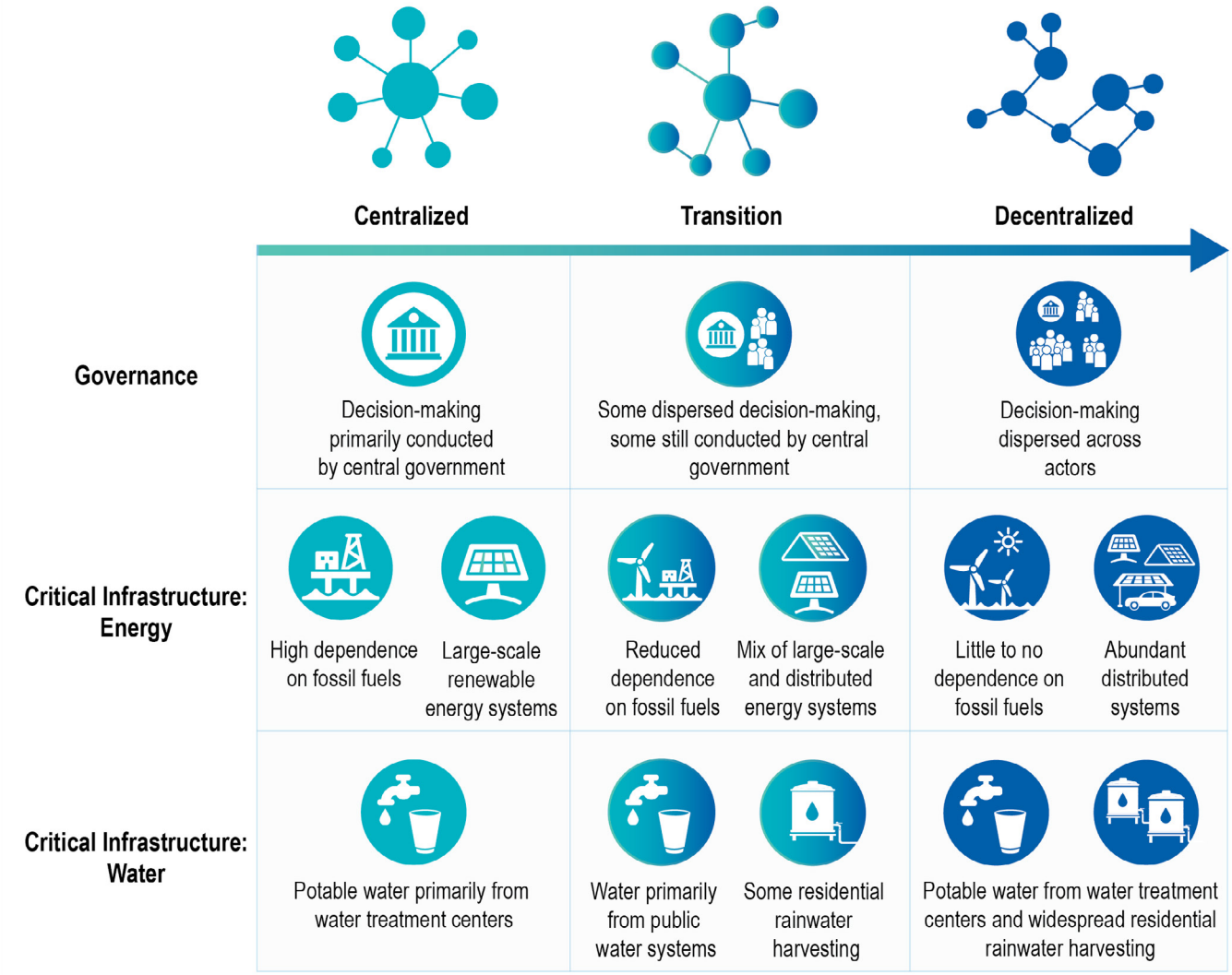
The effects of climate change on infrastructure systems are compounded by human impacts on ecosystems. Ecosystem degradation (e.g., beach erosion, loss of coral reefs or mangroves) is also increasing hazard impacts on infrastructure.[222,223,224,225] Similarly, increased sargassum seaweed[226] can impair infrastructure and render it inoperative, as well as affect the health of the people operating these systems.[227,228,229]

Finally, climate change compounds the stress on already-strained infrastructure systems. Legacy challenges, including systemic lack of investment, mismanagement, and fiscal limitations, undermine the capacity to invest in adaptation activities or to maintain a competitive edge in retaining talent and updating technical capacity.[199,230,231]

Dealing with climate hazards while mitigating other risks will require new thinking about the pitfalls of existing approaches and the potential for a path that allows for better management of resources and service delivery. Highly interdependent infrastructure systems with centralized operation and management structures might be unable to anticipate and adapt to disruptions caused by future climate conditions.[202,232,233] Successful infrastructure adaptation strategies may require restoring natural infrastructure systems (e.g., aquifers, mangrove wetlands, nearshore coral reefs, etc.) for provision of services.[234,235,236] It also may require the adoption of a new paradigm, such as more decentralized infrastructure systems and different models of governance (KM 18.4). For example, household rainwater harvesting protects against prolonged public water system interruptions;[237] sustainable material management reduces pressure on landfills;[238] and microgrids and community solar and household solar systems provide power during inter-

ruptions from the centralized utility (Figure 23.11). These types of decentralized systems can help achieve mitigation targets[239,240,241,242] while also reducing negative health impacts of fossil fuel plants.[243] However, it is important to consider whether or how the adoption of these new systems could exacerbate existing inequities of access to services or to these technologies,[203,244,245] or compete against other land-use opportunities such as farming and housing.[246]

## Decentralizing Infrastructure and Governance




**Strengthening the resilience of infrastructure will require a transition to decentralized systems as well as decentralized modes of governance.**

**Figure 23.11.** For power systems, decentralization means not only investing in more renewable energy systems managed by utilities but also increasing investments in systems managed by communities and households. For water systems, decentralization means increasing investments in water harvesting infrastructure to serve as an alternative. The improvement of governance models, by decentralizing decision-making and resource allocation, will better address climate change threats and current system frailties and problems. Figure credit: University of the Virgin Islands, NOAA NCEI, and CISESS NC.

Infrastructure systems in the Caribbean are at risk of future climate events, but current operation and management approaches increase their vulnerability.[199,200,230] Further research on infrastructure systems, including community-based solutions to climate challenges, could help identify appropriate paths for adaptation.

## Key Message 23.5

## Adaptation Effectiveness Increases When Coupled with Strategic Governance and Planning

Climate adaptation in the US Caribbean is challenging because of multiple interacting factors, including high risk exposure, limited or misaligned funding, insufficient institutional and organizational capacity, and siloed approaches to risk reduction and resilience (*high confidence*). Effective adaptation to support resilience in the US Caribbean could be enhanced through co-development and integration of robust global, regional, and local climate science and risk-based knowledge into planning and implementation, as well as improved governance arrangements (*high confidence*). US Caribbean capabilities in planning and adaptation could be enhanced by strengthening partnerships across the wider Caribbean region and the US mainland (*medium confidence*).

Small islands provide a special case for development and adaptation due to their geographic isolation, complex geographies, diverse cultures, and unique natural resources, compounded by challenges such as their small economies, limited human resources, and costs of utility provision and services.[247,248] Sound policies and institutional capacity are fundamental to effective risk-reduction and disaster response and recovery, as well as the ability to seize current and emerging opportunities for adaptation planning and implementation.

For PR and the USVI, significant financial resources could be made accessible for climate adaptation and comprehensive disaster management, such as through disaster recovery funds, the Community Development Block Grant Mitigation (CDBG-MIT) program, and other federal and nongovernmental organization donors. However, effective adaptation planning is impeded by limited uptake of climate change information in decision-making,[249] weak linkages between programs,[250,251] and insufficient institutional capacity for prioritizing initiatives and designing linked operational systems across multiple organizations.[168,252,253] In addition, adaptation and recovery could be made more efficient and effective by allocating funds that account for social vulnerability metrics.[254]

Policy for climate change planning and adaptation in the US Caribbean has advanced slowly in recent years, as evidenced by the Puerto Rico Climate Change Mitigation, Adaptation, and Resilience Act[255] and Executive Order No. 474-2015: Preparing the Virgin Islands of the United States for Adapting to the Impacts of Climate Change.[256] The Puerto Rico law that created the Expert Advisory Committee on Climate Change mandates that the government allocate funds for its operation and develop a climate change mitigation, adaptation, and resilience plan. Many community-based organizations have also taken action to advance social transformation, climate adaptation, and sustainable development.[257,258,259,260] Organizations in PR include Casa Pueblo (energy); Vieques Love (disaster preparedness, resilience, and capacity building); Mujeres de Islas (sustainable development); Vida Marina (dune restoration); Protectores de Cuenca (watershed restoration); Corporación de Servicios de Salud Primaria y Desarrollo Socioeconómico El Otoao (socioeconomic development and public health); and El Josco Bravo (agriculture). Organizations in the USVI that have taken action on climate change include the University of the Virgin Islands Caribbean Exploratory Research Center (climate change and health), St. Thomas East End Medical Center Corporation (education program on climate change and health), and Foundation for Development Planning Inc. (advocacy on climate change and disaster risk-reduction and participation in public policy process on climate change). Self-organization has also enhanced community trust and cohesiveness.[13]

In the USVI, the US Department of the Interior funded a climate change initiative in 2016 that produced a vulnerability and risk assessment report.[261] The Caribbean Climate Hub and a limited number of civil society organizations supported the initiative. However, there is currently no climate change adaptation program in the USVI, and the inadequate uptake of climate change information for decision-making identified in 2016[249] is still reflected in current public sector policies and programs in both the USVI and PR.[262]

## *Challenges and Opportunities*

Advances in climate adaptation planning and implementation by individuals, communities, and public, private, and civil society organizations are constrained by shifts in demographics, fiscal and socioeconomic conditions and capacities, and high levels of risk exposure in the region (KM 31.2).

In PR and the USVI, vulnerable populations are located in sites exposed to high climatic risk.[20,263] Social determinants of vulnerability include economic instability and limited access to education and healthcare services.[254,264,265,266] This vulnerability amplifies the effects of disasters and undermines the ability to prepare, respond, recover, and adapt.[168,254,267,268]

Between 2000 and 2019, PR was among the territories and countries most affected by extreme weather–related events, and between 2010 and 2020, it registered the highest number of new displacements in the Caribbean,[269,270] largely because its residents are US citizens and can move to the continental US without restrictions.[271]

The US Caribbean experiences both in- and out-migration, which should be considered in planning and adaptation, as migrants require permanent or temporary shelter and essential services.[272] Progress in policy, programs, and implementation has been made, but the dynamics of intraregional migration are not fully understood or addressed.[270]

Decision-making processes and program delivery mechanisms typically involve multiple institutions, including civil society organizations. However, these public and private organizations often work in silos or with limited coordination or collaboration. The effectiveness of these mixed-delivery systems would be significantly improved through enhancements to coordination mechanisms, improved institutional processes, and increased investment in human resources to understand and manage the connected processes and systems (Ch. 31).[42,251,262,273,274] Similarly, overcoming the limitations in the institutional capacity to develop and manage federal grants will help advance adaptation actions in PR and the USVI.[275]

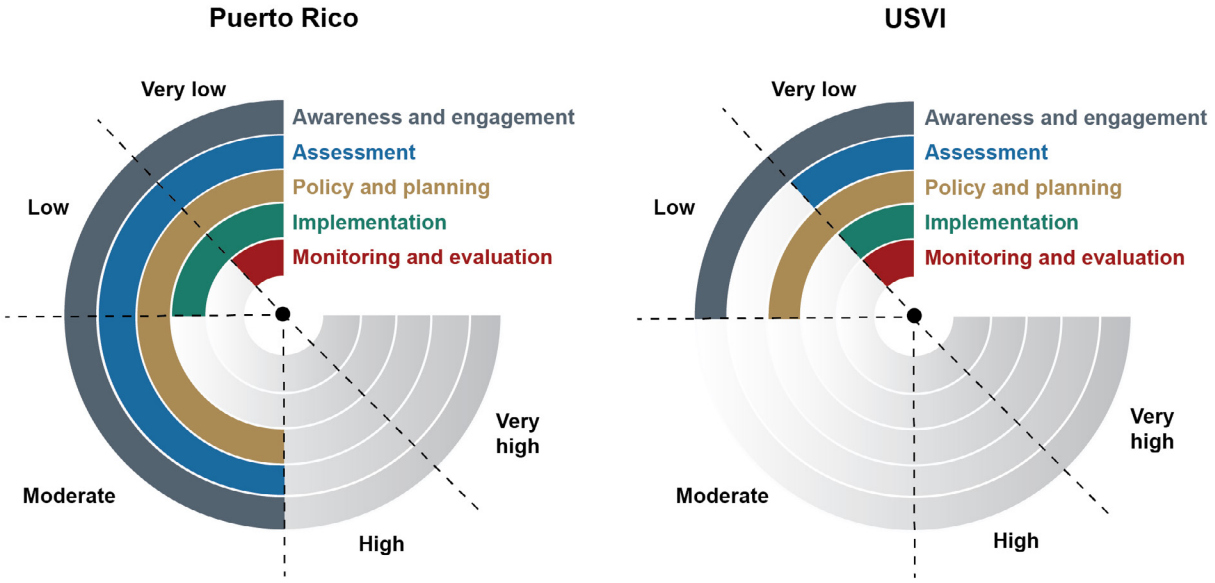
The physical separation of the US Caribbean from the mainland makes disaster response more complex and difficult.[253] Recent reports on the response to Hurricanes Irma and Maria highlight the need for improved planning processes and delivery systems in the relevant federal agencies.[276,277] Ensuring that federal policies and programs are appropriate to local physical conditions and institutional environments and include flexibility to account for future shocks and disturbances could improve disaster response and recovery, as well as climate adaptation action. Policies and program designs that incorporate sustainable land management approaches could reduce vulnerabilities associated with the location of infrastructure and housing in coastal areas and flood zones, water and food insecurity, and degradation of ecological systems. Enhanced alignment of federal and local programs could improve project, program, and development outcomes in the two territories. The government has a fundamental role in creating an appropriate enabling environment for sustainable development—that is, the social ecosystem created by the interplay of policies, laws, institutions, and processes that influence the development of a country. Therefore, ongoing investment in the capacity of government could help ensure that it has the competence to formulate and deliver public policy, maintain significant decision-making capabilities, maintain appropriate and effective governing systems, and develop resilience to shocks.[199,252,278,279,280,281,282]

Current risk-mitigation and emergency response programs focus predominantly on preparedness, response, and recovery—only three of the four phases of a comprehensive disaster management program. The fourth phase is prevention and mitigation, and it is in this phase that economic, legal, sociopolitical, institutional, and other measures are integrated to reduce vulnerability and strengthen resilience.[283,284] In this context, building resilience to disasters and climate change could be enhanced by improving institutional capacity for risk assessment and management.

Both PR Act 33-2019 and USVI Executive Order 474-2015 provide governance frameworks that facilitate coordinated planning and participatory decision-making that involve the public, private, and civil society sectors and the general public. Current federal funding streams available to the territories under the CDBG-MIT program also present an opportunity to advance disaster risk-reduction strategies by focusing more on mitigation and prevention. Modification of the current plans for the USVI and Puerto Rico would make better use of this opportunity.[285]

In the USVI and PR, varying levels of progress have been made across the key elements of climate adaptation (Figure 23.12). This progress reflects the reality that adaptation is an ongoing process that requires evolving governance arrangements to facilitate engagement by all of society.

## Status of Adaptation Action




**Adaptation action in Puerto Rico and the US Virgin Islands reflects different starting times and available capacity.**

**Figure 23.12.** The figure illustrates progress in adaptation action in Puerto Rico and the US Virgin Islands. The colored bars in the charts show the level of progress for each key element of climate adaptation. Adaptation is presented as a continuous process in which multiple elements may overlap or advance simultaneously. Accelerating adaptation action in both territories would reduce risk and enhance resilience. Figure credit: NOAA/Lynker and Foundation for Development Planning Inc. See figure metadata for additional contributors.

Monitoring, research, and action on regional changes to weather systems, ocean health, and terrestrial and coastal ecosystems may be beyond the financial means of individual island states and territories, underscoring the need for pooling of resources and experiences across the region. Many formal and nonformal relationships exist between institutions, governments, and professional associations in the US Caribbean and other Caribbean countries, which provide opportunities for improving climate adaptation actions through stronger regional collaboration.

# Traceable Accounts

## *Process Description*

This chapter was written by a multidisciplinary team of 22 authors that was built in August and September 2021 according to inclusive criteria that sought a diversity of voices by gender, ethnicity, discipline, career stage, knowledge, and geography. Approximately half of the authors work mainly in Puerto Rico (PR), 35% in both US territories, and 15% in the US Virgin Islands (USVI). Sixty percent of authors represent academia, followed by the public sector (about 20%), nongovernmental organizations, and the private sector. The authors are Hispanic- or Latino-Spanish speakers, Afro-Caribbean Black English speakers, and White alone or combined with other races.

Starting in September 2021, the team held weekly all-author meetings to build relationships and capacity. The authors worked in distributed writing teams, each responsible for leading the narrative in each topic and providing evidence supported with literature. On January 19, 2022, the Caribbean chapter hosted a public engagement workshop with 90 participants. Since January 2022, the team continued holding weekly meetings where programmatic and technical issues were discussed. Each Key Message writing team and the chapter lead held weekly meetings to discuss thematic issues, figure development, and more in-depth discussions related to each Key Message.

## Key Message 23.1

## Climate-Driven Extreme Events Exacerbate Inequities and Impact Human Health and Well-Being

### Description of Evidence Base

This topic combines the most recent peer-reviewed information and gray literature on assessment of climate change impacts on the health of people in the US Caribbean. The peer-reviewed literature came from a range of sources.[14,42,50,52,56,59,60,61,62,63,64,80,81,210] The gray literature and reports sourced information from local databases in US Caribbean government agencies and surveys, as well as from databases and other reports.[53,54,67,286] US Census reports lay the foundation for the challenges with descriptions of high levels of poverty and incomes below the US median in both Puerto Rico and the USVI. The literature describing the background information regarding the history of US Caribbean populations being disadvantaged and underserved is documented for the USVI in the needs assessment conducted by Michael et al. (2019)[42] following the 2017 hurricanes; it also provides a combination of local and federal data and information indicating challenges with access to and the extent of services to significant portions of the population before and after the hurricanes. Similar assessments for Puerto Rico have been done by Maldonado et al. (2021)[287] (residential security and community relocation), Seara et al. (2020)[288] (fishing community perception of climate impacts), and Boger et al. (2019)[44] (cultural heritage and traditional knowledge). The relevance of the links between cultural and traditional resources and well-being of people are reported in Boger et al. (2019);[44] Dawson (2013);[289] Finneran (2017);[290] Kohler and Rockman (2020);[291] Perdikaris et al. (2021);[292] and Rockman and Hritz (2020).[293]

There is strong evidence[23,81] in Puerto Rico that extreme heat episodes and extreme rainfall events are increasing in frequency, intensity, and duration, posing the threat of increased incidence of heat-related illness and death, but such evidence is more limited for the USVI at this time. Data on underestimation of

mortality was presented for Puerto Rico specifically in Santos-Burgoa et al. (2018)[56] and in NCHS (2019)[294] in the context of the COVID-19 pandemic. The quantification for USVI is not available for the period after Hurricane Maria.

## Major Uncertainties and Research Gaps

Post-disaster settings present opportunities for researchers and for developers, often to the detriment of local or impacted communities.[292,295] Louis-Charles et al. (2020)[36] call for the need to pay closer attention to the ethics of engagement between, on the one hand, external researchers, agencies, and investment interests, and, on the other, local communities in the Caribbean. Although there have been popular claims calling out the damages of post-disaster gentrification in the media, social media, and popular music, not much research has been conducted on how disaster capitalism exacerbates injustices and cultural erasure in Puerto Rico and the USVI. Elders and Traditional Knowledge highlight concerns with rates of migration of youth and disarticulation of traditional communities that still would benefit from further research.[296]

While research on aerosol and aeroallergen distribution and health impacts has been conducted in Puerto Rico, this association has not yet been quantified in the USVI.

Reports[42,51] and peer-reviewed literature describe impacts of extreme weather and the efforts or needs to mitigate or adapt activities in both Puerto Rico and the USVI.[297] Strengthened education and adaptation outreach efforts could help address issues with behavioral health, noncommunicable disease burdens, and other challenges.

The impact of sargassum algal mats reaching the coasts of the US territories is uncertain. Evidence from other Caribbean islands suggests that this phenomenon will contribute to worsening air quality, ecosystem health, and public health in coastal areas. There are some initial initiatives on an early warning system for Saharan dust, extreme heat, and public health, yet preparedness of the public health sector to mitigate illnesses is still low (and lower in the USVI than in PR). There are uncertainties related to Saharan dust clouds and how climate change will affect seasonality, patterns, concentration, and dust distribution. There are still uncertainties as to why excess mortality happens for extended periods after a natural event; the understanding of these mechanisms requires the identification of the cause-specific mortality and the different conditions leading to death, including infrastructure, critical building capacity, housing, and living conditions. Such an approach is currently being advanced in a project led by the National Institute of Standards and Technology.[298]

## Description of Confidence and Likelihood

There is *high confidence* that climate-related extreme weather events contribute to loss of quality of life and well-being in the US Caribbean. Long histories of colonization, generational trauma, and systemic inequality shape the ability of the US Caribbean peoples to maintain health, quality of life, and overall individual and social well-being (*high confidence*). The level of local and federal research and reports following Hurricanes Irma and Maria in 2017 included information on trends and also identified significant changes and challenges with general health, support services, mental health and well-being in general. In addition, it was noted that the conditions that supported the poor outcomes are major challenges for communities in both PR and the USVI. More frequent heat episodes and powerful hurricanes are expected to increase in the region due to human-induced climate change, affecting public health unless clear and urgent adaptation measures take place (*high confidence*). Climate conditions are favorable for vector-borne diseases (e.g., dengue, Zika, and chikungunya) and human zoonotic diseases (e.g., leptospirosis) in the US Caribbean (*high confidence*). However, many behavioral factors play a confounding and important role (e.g., life-concurrent events, social distancing, age, exposure) in the spread of these diseases. There is *high confidence* in the data and methods in the estimation of the excess mortality in Puerto Rico from Hurricane Maria, and such estimates are now in the official NOAA reports.[299]

## Key Message 23.2

## Ecology and Biodiversity Are Unique and Vulnerable

### Description of Evidence Base

This topic reviews and synthesizes the most up-to-date assessments of climate change impacts on biodiversity, ecosystems, and ecosystem services in the US Caribbean region. The review included gray literature alongside peer-reviewed literature. The peer-reviewed literature considered strong resources from academic and scholarly journals such as the *Journal of Ecology*; *Biological Conservation*; *American Journal of Marine Science*; *Sustainability Science*; *Ecological Indicators*; *Estuarine, Coastal and Shelf Science*; and *Ecosystem Consequences of Soil Warming*. The gray literature included reports, documents, and white papers from federal and local agencies (USDA, USGS, FEMA, US Global Change Research Program, Puerto Rico Department of Natural and Environmental Resources), government entities (Puerto Rico and US Virgin Islands Taskforce), academia (University of Puerto Rico, University of the Virgin Islands), and nonprofit organizations.

The preliminary literature review established and confirmed the observed ecosystem- and biodiversity-level changes in response to climate change due to direct impacts from climate drivers[20,118,123,125,130,136] and the lack of effective adaptation strategies, policies, and measures.[141] Most of the comprehensive assessments reviewed illustrated the rapid changes of habitats, species, and abundance.[131]

### Major Uncertainties and Research Gaps

Both territories experience weather- and climate change–related hazards such as drought, sea level rise, coastal flooding, and erosion. However, the amount of climate research, observations, assessments, and modeling (prediction) are greater in PR than in the USVI. It would be necessary to gather knowledge and information from local agencies, institutions, community-based organizations, and even unpublished information to address existing and pressing gaps in the understanding of climate impacts on biodiversity and ecosystems in the USVI.

### Description of Confidence and Likelihood

There is *high confidence* that the synergistic effects of climate and non-climate stressors are impacting ecosystem goods and services, given the expanding literature with regional examples of these changes. As documented in federal, regional, and local climate change assessment reports, climate and non-climate stressors are *very likely* to persist and become more severe, further accelerating ecosystem degradation and aggravating their service efficiency. These assessment reports also highlight the dependence of the US Caribbean residents on ecosystem services for their well-being and livelihood (*high confidence*), hence the need to safeguard these services. Based on a broad range of evidence, there is *high confidence* that maintaining ecosystem functionality will require integrating effective local-level adaptation and mitigation strategies. However, given the lack of literature on implemented adaptation strategies, there is *medium confidence* that local-level adaptation and mitigation strategies could reduce and manage the risks of climate change on coastal and terrestrial ecosystems.

## Key Message 23.3

## Climate Change Threatens Water and Food Security

### Description of Evidence Base

The discussion of the vulnerability of the US Caribbean food and water systems to climate change is based on observations within the islands and projected changes in the regional and global climate.[10,12,20,21,23,24,25] Localized threats to water and food security include changes in drought intensity, frequency, or duration[20,21] and tropical cyclone rainfall rates and intensity.[24] There is mounting evidence of the impact of climate-related extreme events on the food and water system based on measurements, local knowledge, and published and gray literature.[149,152,168,200,300] There is strong evidence that both hurricanes and drought are major issues for island food and water systems, as illustrated by the impacts of Hurricanes Irma, Maria, and Fiona[168] and the 2014–2016 drought.[300] The direct and cascading impacts of these climate stressors with additional compounding problems, especially sea level rise, are a concern for food and water systems.[165] The literature on direct climate impacts to certain sectors such as crops and livestock is widely available[156,185] for Puerto Rico but is limited for the USVI. The evidence is limited when specifically considering island freshwater and food availability and is mostly available through evidence captured by the drought information system reports.[301] There are no systematic studies that quantify the cascading and compounding impacts of these hazards.

### Major Uncertainties and Research Gaps

The lack of availability of high-resolution climate change projections that better resolve the island climates is a major research gap for understanding plausible future changes in the island climates. Major uncertainties exist with respect to the role of the island terrain and land-use and land-cover change as the climate warms.[21] This research gap is larger for the USVI than for PR. Another modeling challenge and research gap is how future tropical cyclones may interact with small islands like PR and the USVI, especially as rainfall intensity increases in a warmer climate, with cascading impacts on food and water systems. The association between natural hazards and decreased food security or diet diversity in PR and the USVI is another research gap.[302] For the USVI, there is a noted gap of statistics and scientific impact studies on food production and water use. An area of research not discussed is the impact of climate change and major storms on Puerto Rico and the USVI. While there are some reports that document the impact of climate change on fisheries within the Caribbean basin, there are fewer studies that assess the impacts for Puerto Rico and the USVI.[303,304] The role of community-based efforts for mitigating food and water insecurity, as well as the importance of local and Indigenous knowledge to these ends (KMs 30.1, 30.5), has been poorly researched in the US Caribbean and deserves further attention. More information is needed to better assess the impact and response to extreme climate events.[305] Finally, there are research gaps in the compounding and cascading impacts generated by climate change in both Puerto Rico and the USVI.[168]

### Description of Confidence and Likelihood

In the first statement of the Key Message, there is *high confidence* that the US Caribbean food and water systems will become more vulnerable as the climate warms, in part because extreme meteorological events like hurricanes and droughts are *likely* to become stronger and more severe in the future. There is *high confidence* that climate change at both global and regional scales is important because the islands are heavily reliant on imported foods. However, climate change projections at the scale of the islands are limited to a few studies, allowing *medium confidence* in predictions of local direct impacts of climate change on freshwater availability for the region. While improved knowledge will enhance adaptation, the authors have *medium confidence* because the adaptation process also relies on social and economic changes. The evidence base was not sufficient to determine quantitative probabilities for the second through the fourth statements in this Key Message; thus, no likelihood is specified.

## Key Message 23.4

### Infrastructure and Energy Are Vulnerable, but Decentralization Could Improve Resilience

#### Description of Evidence Base

The vulnerability of US Caribbean infrastructure systems to climate change is based on observations of impacts of recent climatic events within the islands and projected changes in the regional and global climate. The evidence to support current vulnerability of systems and future climate vulnerability is mostly based on documents from the gray literature, including reports from federal agencies and/or sponsored by federal or territorial agencies[199,200,204,230] following Hurricanes Irma and Maria. The published literature and reports are not as rich as for locations in the continental US. The description of the need for a paradigm change in the governance of infrastructure systems is based on a number of peer-reviewed journal articles describing observations of the limits of current governance systems, as well as more academic journal articles addressing best practices for building resilient infrastructure systems. There is very little published literature on the effects of governance on the ability to adapt, especially in the US Caribbean.

#### Major Uncertainties and Research Gaps

The availability of more structural and system operation assessments of the vulnerability of infrastructure systems to flood and wind events is a major research gap, because most assessments are made by looking at the presence or absence of a system component in a flood zone. Often it is unclear whether the system component can be accessed or operated, or even whether it may have been rendered unsafe by previous mitigation activities that took place. Another gap is the lack of availability of public geodatabases of infrastructure systems. The region is also missing flood maps that take into account future climates. Furthermore, understanding the effectiveness and feasibility of decentralized governance systems for critical infrastructure is a major research gap and need, as much of the current literature demonstrates the limits of centralized systems in the Caribbean. Finally, the lack of easily accessible data on water and power consumption, traffic patterns, and other ways that humans use infrastructure systems is a major data gap that needs to be filled so that adaptation strategies can be developed to mitigate against any disruption in the delivery of services.

#### Description of Confidence and Likelihood

Based on the level of damage incurred during Hurricanes Irma and Maria (2017) and Hurricane Fiona (2022), as well as the post-2017 hurricane reports published by the government and federal agencies, there is *high confidence* that infrastructure systems in the US Caribbean are suffering from a lack of maintenance and investment and that climate change has created profound risks for the US Caribbean's critical infrastructure, especially as extreme meteorological events become more *likely* in the future. There is *high confidence* that dependence on fossil fuel imports increases energy insecurity, based on numerous reports from the gray literature and the recent fiscal difficulties experienced by the public utilities in both Puerto Rico and the USVI.

Given the lack of stability of the public utilities, as described in government and federal agency reports, and given the relative lack of long-term data on the effectiveness of solar electric systems as an alternative to centralized systems to provide power to communities during and outside of disasters, there is *medium confidence* that decentralization of system production and distribution, and *medium confidence* that decarbonization and shared governance, will *likely* help limit residents' vulnerability to health and other risks associated with the loss of essential services programs.

## Key Message 23.5

### Adaptation Effectiveness Increases When Coupled with Strategic Governance and Planning

#### Description of Evidence Base

The evidence to support the Key Message consists of articles in peer-reviewed journals, research publications by universities, technical papers, assessment reports produced by or on behalf of the federal and territorial governments, executive orders and legislation passed by the territorial governments, and technical reports by Caribbean and global intergovernmental organizations.

The peer-reviewed journals were classified with impact factors that range from 3.20 to 9.5, indicating that the journals are trustworthy. The documents prepared or funded by federal and territorial governments underpin the conclusions regarding challenges of various levels of government for effective planning and adaptation.[148,249,252,253,276,277,279] Literature that supports the conclusions regarding effective adaptation action through improved governance arrangements and coproduction with community organizations includes McGinley et al (2022),[168] Filantropia Puerto Rico Inc. (2022),[258] and Towe et al. (2020).[262] The gray literature also includes publications by research institutions such as the National Institute of Building Sciences, the International Council for Local Environmental Initiatives–Local Governments for Sustainability USA, the University of the Virgin Islands, and the University of Colorado.

Since the publication of the Fourth National Climate Assessment in 2018, climate adaptation action is increasingly being informed by high-quality data, policies, laws, white papers, and technical reports prepared by the governments of the two territories, Puerto Rico's Expert Advisory Committee on Climate Change, the Puerto Rico Climate Change Council, the Governors' Institute on Community Design, academia, scientists, and community-based organizations.

#### Major Uncertainties and Research Gaps

A large body of literature is available globally and for the wider Caribbean on the benefits of local adaptation through coproduction. For the US Caribbean, although there are participatory efforts, mostly from the nonprofit sector and many supported by academia, the published literature is sparse. As such, additional research and evaluation on the capacity requirements and design for collective action would enhance implementation.

#### Description of Confidence and Likelihood

Statements about the challenges of climate adaptation in the US Caribbean due to multiple interacting factors—including high risk exposure, limited or misaligned funding, insufficient institutional and organizational capacity, and siloed approaches to risk reduction and resilience—are based on extensive analysis of peer-reviewed papers; federal, regional, and local technical reports; and the onsite experience of the multidisciplinary, multisectoral team of 22 authors of this chapter. Authors had the opportunity to deal with, study, and/or assess these diverse interacting factors that are related to climate adaptation in the US Caribbean from diverse points of view. As a result, authors have *high confidence* in the first statement of the Key Message.

On-site experience, data, and numerous studies with consistent findings support the idea that US Caribbean adaptation could be enhanced through co-development and integration of robust global, regional, and local climate science and risk-based knowledge into planning and implementation, as well as improved governance, resulting in *high confidence* in the second part of the Key Message.

Based on a smaller number of studies but further deliberation among our author team, the statements about how US Caribbean capabilities in planning and adaptation can be enhanced by strengthening partnerships across the wider Caribbean region and the US mainland is assigned *medium confidence*.

# References


1. Gould, W.A., E.L. Díaz (co-leads), N.L. Álvarez-Berríos, F. Aponte-González, W. Archibald, J.H. Bowden, L. Carrubba, W. Crespo, S.J. Fain, G. González, A. Goulbourne, E. Harmsen, E. Holupchinski, A.H. Khalyani, J. Kossin, A.J. Leinberger, V.I. Marrero-Santiago, O. Martínez-Sánchez, K. McGinley, P. Méndez-Lázaro, J. Morell, M.M. Oyola, I.K. Parés-Ramos, R. Pulwarty, W.V. Sweet, A. Terando, and S. Torres-González, 2018: Ch. 20. U.S. Caribbean. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 809–871. https://doi.org/10.7930/nca4.2018.ch20

2. American Community Survey, 2015: Data Profiles. U.S. Census Bureau. https://www.census.gov/acs/www/data/data-tables-and-tools/data-profiles/2015/

3. DeWaard, J., J.E. Johnson, and S.D. Whitaker, 2020: Out-migration from and return migration to Puerto Rico after Hurricane Maria: Evidence from the consumer credit panel. *Population and Environment*, **42** (1), 28–42. https://doi.org/10.1007/s11111-020-00339-5

4. Mayol-García, Y.H., 2020: Pre-hurricane linkages between poverty, families, and migration among Puerto Rican-origin children living in Puerto Rico and the United States. *Population and Environment*, **42** (1), 57–78. https://doi.org/10.1007/s11111-020-00353-7

5. U.S. Census Bureau, 2010: QuickFacts: United States. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/quickfacts/fact/table/us/pst045221

6. U.S. Census Bureau, 2020: data.census.gov. U.S. Department of Commerce, U.S. Census Bureau. https://data.census.gov/table

7. Rodríguez-Díaz, C.E., 2018: Maria in Puerto Rico: Natural disaster in a colonial archipelago. *American Journal of Public Health*, **108** (1), 30–32. https://doi.org/10.2105/ajph.2017.304198

8. HUD, 2017: Office of Policy Development and Research. U.S. Department of Housing and Urban Development. https://www.hud.gov/programdescription/pdr

9. U.S. Census Bureau, 2020: Post-Enumeration Surveys. U.S. Department of Commerce, U.S. Census Bureau. https://data.census.gov/all?y=2020&d=DEC+Decennial+Post-Enumeration+Survey

10. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

11. McPhillips, L.E., H. Chang, M.V. Chester, Y. Depietri, E. Friedman, N.B. Grimm, J.S. Kominoski, T. McPhearson, P. Méndez-Lázaro, E.J. Rosi, and J. Shafiei Shiva, 2018: Defining extreme events: A cross-disciplinary review. *Earth's Future*, **6** (3), 441–455. https://doi.org/10.1002/2017ef000686

12. Runkle, J., K.E. Kunkel, L.E. Stevens, S.M. Champion, D.R. Easterling, A. Terando, L. Sun, B.C. Stewart, G. Landers, and S. Rayne, 2022: Puerto Rico and the U.S. Virgin Islands State Climate Summary 2022. NOAA Technical Report NESDIS 150-PR. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD, 5 pp. https://statesummaries.ncics.org/chapter/pr/

13. Holladay, P., P. Méndez-Lázaro, and K. Brundiers, 2021: From hurricanes to pandemics: Community-based transformation and destination resilience in Utuado, Puerto Rico. *Journal of Sustainability and Resilience*, **1** (2), 1–6. https://digitalcommons.usf.edu/jsr/vol1/iss2/1

14. Méndez-Lázaro, P.A., Y.M. Bernhardt, W.A. Calo, A.M. Pacheco Díaz, S.I. García-Camacho, M. Rivera-Lugo, E. Acosta-Pérez, N. Pérez, and A.P. Ortiz-Martínez, 2021: Environmental stressors suffered by women with gynecological cancers in the aftermath of Hurricanes Irma and María in Puerto Rico. *International Journal of Environmental Research and Public Health*, **18** (21), 11183. https://doi.org/10.3390/ijerph182111183

15. Rivera-Collazo, I.C., 2021: Climate change and archaeological sites: A case study for partnering cultural heritage and climate action. In: *Stemming the Tide: Global Strategies for Sustaining Cultural Heritage through Climate Change*. Rushfield, R., Ed. Smithsonian Institution Scholarly Press, Washington, DC, 25–38. https://doi.org/10.5479/si.14750727

16. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

17. FOMBPR, 2022: 2022 Fiscal Plan for Puerto Rico: Restoring Growth and Prosperity. The Financial Oversight and Management Board for Puerto Rico, 355 pp. https://oversightboard.pr.gov/fiscal-plans-2/

18. Lamba-Nieves, D., Sergio M. Marxuach, and R. Torres, 2021: PROMESA: A Failed Colonial Experiment? Center for a New Economy. https://grupocne.org/2021/06/29/promesa-a-failed-colonial-experiment/

19. U.S. Department of the Treasury, 2018: Puerto Rico's Economic and Fiscal Crisis. U.S. Department of the Treasury, 7 pp. https://www.supremecourt.gov/opinions/urls_cited/ot2019/18-1334/18-1334-1.pdf

20. Puerto Rico Climate Change Council, 2022: Puerto Rico's State of the Climate 2014–2021: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate. Puerto Rico Coastal Zone Management Program, Department of Natural and Environmental Resources, NOAA Office of Ocean and Coastal Resource Management, San Juan, PR. https://www.drna.pr.gov/wp-content/uploads/2022/10/PR_StateOfTheClimate_2014-2021_PRCCC-09-2022.pdf

21. Bowden, J.H., A.J. Terando, V. Misra, A. Wootten, A. Bhardwaj, R. Boyles, W. Gould, J.A. Collazo, and T.L. Spero, 2021: High-resolution dynamically downscaled rainfall and temperature projections for ecological life zones within Puerto Rico and for the U.S. Virgin Islands. *International Journal of Climatology*, **41** (2), 1305–1327. https://doi.org/10.1002/joc.6810

22. Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ch. 9. Ocean, cryosphere and sea level change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1211–1362. https://doi.org/10.1017/9781009157896.011

23. Keellings, D. and J.J. Hernández Ayala, 2019: Extreme rainfall associated with Hurricane Maria over Puerto Rico and its connections to climate variability and change. *Geophysical Research Letters*, **46** (5), 2964–2973. https://doi.org/10.1029/2019gl082077

24. Knutson, T., S.J. Camargo, J.C.L. Chan, K. Emanuel, C.H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2020: Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, **101** (3), 303–322. https://doi.org/10.1175/bams-d-18-0194.1

25. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

26. Bell, G.D. and M. Chelliah, 2006: Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. *Journal of Climate*, **19** (4), 590–612. https://doi.org/10.1175/jcli3659.1

27. Philander, G., 1989: El Niño and La Niña. *American Scientist*, **77** (5), 451–459. http://www.jstor.org/stable/27855934

28. Torres-Valcárcel, A.R., 2018: Teleconnections between ENSO and rainfall and drought in Puerto Rico. *International Journal of Climatology*, **38** (S1), e1190–e1204. https://doi.org/10.1002/joc.5444

29. Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck, 2003: Ch. 1. An overview of the North Atlantic Oscillation. In: *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*. Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck, Eds. American Geophysical Union, 1–35. https://doi.org/10.1029/134gm01

30. Martinez, C., Y. Kushnir, L. Goddard, and M. Ting, 2020: Interannual variability of the early and late-rainy seasons in the Caribbean. *Climate Dynamics*, **55** (5), 1563–1583. https://doi.org/10.1007/s00382-020-05341-z

31. Mote, T.L., C.A. Ramseyer, and P.W. Miller, 2017: The Saharan Air Layer as an early rainfall season suppressant in the Eastern Caribbean: The 2015 Puerto Rico drought. *Journal of Geophysical Research: Atmospheres*, **122** (20), 10966–10982. https://doi.org/10.1002/2017jd026911

32. Reed, K.A., J.T. Bacmeister, J.J.A. Huff, X. Wu, S.C. Bates, and N.A. Rosenbloom, 2019: Exploring the impact of dust on North Atlantic hurricanes in a high-resolution climate model. *Geophysical Research Letters*, **46** (2), 1105–1112. https://doi.org/10.1029/2018gl080642

33. Cashman, A., 2014: Water security and services in the Caribbean. *Water*, **6** (5), 1187–1203. https://doi.org/10.3390/w6051187

34. Watson, A., S. Ganapati, A. Grossman, J. Trtanj, N. Arbour, I. Torres, and A.M. Stewart-Ibarra, 2022: Not what the doctor ordered: Prioritizing transdisciplinary science on climate, environment and health in the Latin American and Caribbean region. *PLoS Climate*, **1** (4), e0000025. https://doi.org/10.1371/journal.pclm.0000025

35. Gahman, L. and G. Thongs, 2020: Development justice, a proposal: Reckoning with disaster, catastrophe, and climate change in the Caribbean. *Transactions of the Institute of British Geographers*, **45** (4), 763–778. https://doi.org/10.1111/tran.12369

36. Louis-Charles, H.M., R. Howard, L. Remy, F. Nibbs, and G. Turner, 2020: Ethical considerations for postdisaster fieldwork and data collection in the Caribbean. *American Behavioral Scientist*, **64** (8), 1129–1144. https://doi.org/10.1177/0002764220938113

37. McHarg, E., E. Mengo, L. Benson, J. Daniel, A. Joseph-Witzig, P. Posen, and T. Luisetti, 2022: Valuing the contribution of blue carbon to small island developing states' climate change commitments and COVID-19 recovery. *Environmental Science & Policy*, **132**, 13–23. https://doi.org/10.1016/j.envsci.2022.02.009

38. Winters, Z.S., T.L. Crisman, and D.T. Dumke, 2022: Sustainability of the water-energy-food nexus in Caribbean small island developing states. *Water*, **14** (3). https://doi.org/10.3390/w14030322

39. Iwama, A.Y., F. Araos, J. Anbleyth-Evans, V. Marchezini, A. Ruiz-Luna, F. Ther-Ríos, G. Bacigalupe, and P.E. Perkins, 2021: Multiple knowledge systems and participatory actions in slow-onset effects of climate change: Insights and perspectives in Latin America and the Caribbean. *Current Opinion in Environmental Sustainability*, **50**, 31–42. https://doi.org/10.1016/j.cosust.2021.01.010

40. Latulippe, N. and N. Klenk, 2020: Making room and moving over: Knowledge co-production, Indigenous knowledge sovereignty and the politics of global environmental change decision-making. *Current Opinion in Environmental Sustainability*, **42**, 7–14. https://doi.org/10.1016/j.cosust.2019.10.010

41. PAHO, 2019: Caribbean Action Plan on Health and Climate Change. Pan American Health Organization, Washington, DC. https://iris.paho.org/bitstream/handle/10665.2/38566/pahocde19007_eng.pdf?sequence=19&isallowed=y

42. Michael, N., J.M. Valmond, L.E. Ragster, D.E. Brown, and G.B. Callwood, 2019: Community Needs Assessment: Understanding the Needs of Vulnerable Children and Families in the US Virgin Islands Post Hurricanes Irma and Maria. University of the Virgin Islands, School of Nursing, Caribbean Exploratory Research Center, St. Thomas, USVI. https://cfvi.net/wp-content/uploads/2019/03/CFVI-CERC-Community-Needs-Assessment-E-Report_February-2019_Bookmarked.pdf

43. WHO, 2021: Tripartite and UNEP Support OHHLEP's Definition of "One Health". World Health Organization. https://www.who.int/news/item/01-12-2021-tripartite-and-unep-support-ohhlep-s-definition-of-one-health

44. Boger, R., S. Perdikaris, and I. Rivero-Collazo, 2019: Cultural heritage and local ecological knowledge under threat: Two Caribbean examples from Barbuda and Puerto Rico. *Journal of Anthropology and Archaeology*, **7** (2), 1–14. https://doi.org/10.15640/jaa.v7n2p1

45. Dunnavant, J.P., A.O. Flewellen, A. Jones, A. Odewale, and W. White, 2018: Assessing heritage resources in St. Croix post-Hurricanes Irma and Maria. *Transforming Anthropology*, **26** (2), 157–172. https://doi.org/10.1111/traa.12130

46. Rivera-Collazo, I.C., 2020: Severe weather and the reliability of desk-based vulnerability assessments: The impact of Hurricane Maria to Puerto Rico's coastal archaeology. *The Journal of Island and Coastal Archaeology*, **15** (2), 244–263. https://doi.org/10.1080/15564894.2019.1570987

47. USACE, 2022: Antilles Area Office. U.S. Army Corps of Engineers, Jacksonville District, accessed September 29, 2022. https://www.saj.usace.army.mil/about/divisions-offices/antilles-office/

48. Horowitz, L.S., 2022: "Conflicts of interests" within and between elite assemblages in the legal production of space: Indigenous cultural heritage preservation and the Dakota Access Pipeline. *The Geographical Journal*, **188** (1), 91–108. https://doi.org/10.1111/geoj.12421

49. Kaenzig, R. and E. Piguet, 2014: Ch. 7. Migration and climate change in Latin America and the Caribbean. In: *People on the Move in a Changing Climate: The Regional Impact of Environmental Change on Migration*. Piguet, E. and F. Laczko, Eds. Springer, Dordrecht, Netherlands, 155–176. https://doi.org/10.1007/978-94-007-6985-4_7

50. Chowdhury, M.A.B., A.J. Fiore, S.A. Cohen, C. Wheatley, B. Wheatley, M.P. Balakrishnan, M. Chami, L. Scieszka, M. Drabin, K.A. Roberts, A.C. Toben, J.A. Tyndall, L.M. Grattan, and J.G. Morris, 2019: Health impact of Hurricanes Irma and Maria on St Thomas and St John, US Virgin Islands, 2017–2018. *American Journal of Public Health*, **109** (12), 1725–1732. https://doi.org/10.2105/ajph.2019.305310

51. Guannel, G., H. Lohmann, and J. Dwyer, 2022: The Public Health Implications of Social Vulnerability in the U.S. Virgin Islands. Natural Hazards Center Public Health Grant Report Series, 23. University of Colorado Boulder, Natural Hazards Center, Boulder, CO. https://hazards.colorado.edu/public-health-disaster-research/the-public-health-implications-of-social-vulnerability-in-the-u-s-virgin-islands

52. Irvin-Barnwell, E., M. Cruz, C. Maniglier-Poulet, J. Cabrera, J.R. Diaz, R.D.L. Cruz Perez, C. Forrester, A. Shumate, J. Mutter, L. Graziano, L.R. Gonzalez, J. Malilay, and M. Raheem, 2020: Evaluating disaster damages and operational status of health-care facilities during the emergency response phase of Hurricane Maria in Puerto Rico. *Disaster Medicine and Public Health Preparedness*, **14** (1), 80–88. https://doi.org/10.1017/dmp.2019.85

53. EPA, 2022: Search for Superfund Sites Where You Live. U.S. Environmental Protection Agency. https://www.epa.gov/superfund/search-superfund-sites-where-you-live

54. EPA, 2015: National Priorities List (NPL) Sites–By State. U.S. Environmental Protection Agency. https://www.epa.gov/superfund/national-priorities-list-npl-sites-state

55. Kishore, N., D. Marqués, A. Mahmud, M.V. Kiang, I. Rodriguez, A. Fuller, P. Ebner, C. Sorensen, F. Racy, J. Lemery, L. Maas, J. Leaning, R.A. Irizarry, S. Balsari, and C.O. Buckee, 2018: Mortality in Puerto Rico after Hurricane Maria. *New England Journal of Medicine*, **379** (2), 162–170. https://doi.org/10.1056/nejmsa1803972

56. Santos-Burgoa, C., J. Sandberg, E. Suárez, A. Goldman-Hawes, S. Zeger, A. Garcia-Meza, C.M. Pérez, N. Estrada-Merly, U. Colón-Ramos, C.M. Nazario, E. Andrade, A. Roess, and L. Goldman, 2018: Differential and persistent risk of excess mortality from Hurricane Maria in Puerto Rico: A time-series analysis. *The Lancet Planetary Health*, **2** (11), 478–488. https://doi.org/10.1016/s2542-5196(18)30209-2

57. Orengo-Aguayo, R., R.W. Stewart, M.A. Arellano, J.L. Suárez-Kindy, and J. Young, 2019: Disaster exposure and mental health among Puerto Rican youths after Hurricane Maria. *JAMA Network Open*, **2** (4), 192619. https://doi.org/10.1001/jamanetworkopen.2019.2619

58. Hall, C., R. Rudowitz, S. Artiga, and B. Lyons, 2018: One Year After the Storms: Recovery and Health Care in Puerto Rico and the U.S. Virgin Islands. Kaiser Family Foundation. https://www.kff.org/medicaid/issue-brief/one-year-after-the-storms-recovery-and-health-care-in-puerto-rico-and-the-u-s-virgin-islands/

59. Calo, W.A., M. Rivera, P.A. Mendez-Lazaro, S.I. Garcia-Camacho, Y.M. Bernhardt Utz, E. Acosta-Perez, and A.P. Ortiz, 2022: Disruptions in oncology care confronted by patients with gynecologic cancer following Hurricanes Irma and Maria in Puerto Rico. *Cancer Control*, **29**, 10732748221114691. https://doi.org/10.1177/10732748221114691

60. Cruz, N.I., E. Santiago, and K. Rodríguez, 2020: The effect of Hurricane Maria on the surgical workload of the UPR-affiliated hospitals. *Puerto Rico Health Sciences Journal*, **39** (2), 195–199. https://pubmed.ncbi.nlm.nih.gov/32663917/

61. Gay, H.A., R. Santiago, B. Gil, C. Remedios, P.J. Montes, J. López-Araujo, C.M. Chévere, W.S. Imbert, J. White, D.W. Arthur, J.K. Horton, R. Jagsi, R. Rabinovich, S. Beriwal, A. Viswanathan, B.A. Erickson, R. Rengan, D. Palma, B.W. Loo, J.A. Kavanaugh, J. Bradley, S.S. Yom, P.M. Harari, and O. Lee Burnett, 2019: Lessons learned from Hurricane Maria in Puerto Rico: Practical measures to mitigate the impact of a catastrophic natural disaster on radiation oncology patients. *Practical Radiation Oncology*, **9** (5), 305–321. https://doi.org/10.1016/j.prro.2019.03.007

62. Kunos, C.A. and P. Ivy, 2019: Leveraging National Cancer Institute programmatic collaboration for uterine cervix cancer brachytherapy in Puerto Rico after Hurricane Maria. *Frontiers in Oncology*, **9**, 414. https://doi.org/10.3389/fonc.2019.00414

63. Lukowsky, L.R., A. Dobalian, K. Kalantar-Zadeh, and C. Der-Martirosian, 2023: Dialysis care for US military veterans in Puerto Rico during the 2017 Atlantic hurricane season. *Disaster Medicine and Public Health Preparedness*, **17**, 187. https://doi.org/10.1017/dmp.2022.63

64. Rodriguez-Rabassa, M., R. Hernandez, Z. Rodriguez, C.B. Colon-Echevarria, L. Maldonado, N. Tollinchi, E. Torres-Marrero, A. Mulero, D. Albors, J. Perez-Morales, I. Flores, J. Dutil, H. Jim, E.M. Castro, and G.N. Armaiz-Pena, 2020: Impact of a natural disaster on access to care and biopsychosocial outcomes among Hispanic/Latino cancer survivors. *Scientific Reports*, **10** (1), 10376. https://doi.org/10.1038/s41598-020-66628-z

65. Ortiz, A.P., W.A. Calo, P. Mendez-Lazaro, S. García-Camacho, A. Mercado-Casillas, J. Cabrera-Márquez, and G. Tortolero-Luna, 2020: Strengthening resilience and adaptive capacity to disasters in cancer control plans: Lessons learned from Puerto Rico. *Cancer Epidemiology, Biomarkers & Prevention*, **29** (7), 1290–1293. https://doi.org/10.1158/1055-9965.epi-19-1067

66. USVI DOH, 2020: 2020 United States Virgin Islands Community Health Assessment. U.S. Virgin Islands Department of Health, Christiansted, USVI. https://doh.vi.gov/community-health-assessment-report

67. NCCDPHP, 2020: Nutrition, Physical Activity, and Obesity: Data, Trends and Maps. Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion. https://www.cdc.gov/nccdphp/dnpao/data-trends-maps/index.html

68. CDC, 2021: Morbidity and Mortality Weekly Report. Centers for Disease Control and Prevention. https://www.cdc.gov/mmwr/index.html

69. Mattei, J., M. Tamez, J. O'Neill, S. Haneuse, S. Mendoza, J. Orozco, A. Lopez-Cepero, C.F. Ríos-Bedoya, L.M. Falcón, K.L. Tucker, and J.F. Rodríguez-Orengo, 2022: Chronic diseases and associated risk factors among adults in Puerto Rico after Hurricane Maria. *JAMA Network Open*, **5** (1), 2139986. https://doi.org/10.1001/jamanetworkopen.2021.39986

70. Ferré, I.M., S. Negrón, J.M. Shultz, S.J. Schwartz, J.P. Kossin, and H. Pantin, 2019: Hurricane Maria's impact on Punta Santiago, Puerto Rico: Community needs and mental health assessment six months postimpact. *Disaster Medicine and Public Health Preparedness*, **13** (1), 18–23. https://doi.org/10.1017/dmp.2018.103

71. Scaramutti, C., C.P. Salas-Wright, S.R. Vos, and S.J. Schwartz, 2019: The mental health impact of Hurricane Maria on Puerto Ricans in Puerto Rico and Florida. *Disaster Medicine and Public Health Preparedness*, **13** (1), 24–27. https://doi.org/10.1017/dmp.2018.151

72. de Jesús Crespo, R., P.M. Lázaro, and S.H. Yee, 2019: Linking wetland ecosystem services to vector-borne disease: Dengue fever in the San Juan Bay Estuary, Puerto Rico. *Wetlands*, **39** (6), 1281–1293. https://doi.org/10.1007/s13157-017-0990-5

73. Johansson, M.A., D.A.T. Cummings, and G.E. Glass, 2009: Multiyear climate variability and dengue—El Niño Southern Oscillation, weather, and dengue incidence in Puerto Rico, Mexico, and Thailand: A longitudinal data analysis. *PLoS Medicine*, **6** (11), 1000168. https://doi.org/10.1371/journal.pmed.1000168

74. Laureano-Rosario, A.E., Andrew P. Duncan, Pablo A. Mendez-Lazaro, Julian E. Garcia-Rejon, Salvador Gomez-Carro, Jose Farfan-Ale, Dragan A. Savic, and Frank E. Muller-Karger, 2018: Application of artificial neural networks for dengue fever outbreak predictions in the northwest coast of Yucatan, Mexico and San Juan, Puerto Rico. *Tropical Medicine and Infectious Disease*, **3** (1), 5. https://doi.org/10.3390/tropicalmed3010005

75. Méndez-Lázaro, P.A., A. Nieves-Santiango, and J. Miranda-Bermúdez, 2014: Trends in total rainfall, heavy rain events, and number of dry days in San Juan, Puerto Rico, 1955–2009. *Ecology and Society*, **19** (2), 50. https://doi.org/10.5751/es-06464-190250

76. Morin, C.W., A.J. Monaghan, M.H. Hayden, R. Barrera, and K. Ernst, 2015: Meteorologically driven simulations of dengue epidemics in San Juan, PR. *PLoS Neglected Tropical Diseases*, **9** (8), 0004002. https://doi.org/10.1371/journal.pntd.0004002

77. Pratt, N. and S. Rajeev, 2018: Leptospira seroprevalence in animals in the Caribbean region: A systematic review. *Acta Tropica*, **182**, 34–42. https://doi.org/10.1016/j.actatropica.2018.02.011

78. Lau, C.L., L.D. Smythe, S.B. Craig, and P. Weinstein, 2010: Climate change, flooding, urbanisation and leptospirosis: Fuelling the fire? *Transactions of the Royal Society of Tropical Medicine and Hygiene*, **104** (10), 631–638. https://doi.org/10.1016/j.trstmh.2010.07.002

79. Di Napoli, C., T. Allen, P.A. Méndez-Lázaro, and F. Pappenberger, 2023: Heat stress in the Caribbean: Climatology, drivers, and trends of human biometeorology indices. *International Journal of Climatology*, **43** (1), 405–425. https://doi.org/10.1002/joc.7774

80. Méndez-Lázaro, P., F.E. Muller-Karger, D. Otis, M.J. McCarthy, and E. Rodríguez, 2018: A heat vulnerability index to improve urban public health management in San Juan, Puerto Rico. *International Journal of Biometeorology*, **62** (5), 709–722. https://doi.org/10.1007/s00484-017-1319-z

81. Méndez-Lázaro, P.A., C.M. Pérez-Cardona, E. Rodríguez, O. Martínez, M. Taboas, A. Bocanegra, and R. Méndez-Tejeda, 2018: Climate change, heat, and mortality in the tropical urban area of San Juan, Puerto Rico. *International Journal of Biometeorology*, **62** (5), 699–707. https://doi.org/10.1007/s00484-016-1291-z

82. Méndez-Lázaro, P., O. Martínez-Sánchez, R. Méndez-Tejeda, E. Rodríguez, E. Morales, and N.S. Cortijo, 2015: Extreme heat events in San Juan Puerto Rico: Trends and variability of unusual hot weather and its possible effects on ecology and society. *Journal of Climatology & Weather Forecasting*, **3**, 135. https://doi.org/10.4172/2332-2594.1000135

83. Clifford, H.M., N.E. Spaulding, A.V. Kurbatov, A. More, E.V. Korotkikh, S.B. Sneed, M. Handley, K.A. Maasch, C.P. Loveluck, J. Chaplin, M. McCormick, and P.A. Mayewski, 2019: A 2000 year Saharan dust event proxy record from an ice core in the European Alps. *Journal of Geophysical Research: Atmospheres*, **124** (23), 12882–12900. https://doi.org/10.1029/2019jd030725

84. Evan, A.T., G.R. Foltz, D. Zhang, and D.J. Vimont, 2011: Influence of African dust on ocean–atmosphere variability in the tropical Atlantic. *Nature Geoscience*, **4** (11), 762–765. https://doi.org/10.1038/ngeo1276

85. Okin, G.S., A.R. Baker, I. Tegen, N.M. Mahowald, F.J. Dentener, R.A. Duce, J.N. Galloway, K. Hunter, M. Kanakidou, N. Kubilay, J.M. Prospero, M. Sarin, V. Surapipith, M. Uematsu, and T. Zhu, 2011: Impacts of atmospheric nutrient deposition on marine productivity: Roles of nitrogen, phosphorus, and iron. *Global Biogeochemical Cycles*, **25** (2). https://doi.org/10.1029/2010gb003858

86. Prospero, J.M., 1999: Long-term measurements of the transport of African mineral dust to the southeastern United States: Implications for regional air quality. *Journal of Geophysical Research: Atmospheres*, **104** (D13), 15917–15927. https://doi.org/10.1029/1999jd900072

87. Prospero, J.M., F.-X. Collard, J. Molinié, and A. Jeannot, 2014: Characterizing the annual cycle of African dust transport to the Caribbean Basin and South America and its impact on the environment and air quality. *Global Biogeochemical Cycles*, **28** (7), 757–773. https://doi.org/10.1002/2013gb004802

88. Prospero, J.M. and O.L. Mayol-Bracero, 2013: Understanding the transport and impact of African dust on the Caribbean Basin. *Bulletin of the American Meteorological Society*, **94** (9), 1329–1337. https://doi.org/10.1175/bams-d-12-00142.1

89. Tong, D.Q., T.E. Gill, W.A. Sprigg, R.S. Van Pelt, A.A. Baklanov, B.M. Barker, J.E. Bell, J. Castillo, S. Gassó, C.J. Gaston, D.W. Griffin, N. Huneeus, R.A. Kahn, A.P. Kuciauskas, L.A. Ladino, J. Li, O.L. Mayol-Bracero, O.Z. McCotter, P.A. Méndez-Lázaro, P. Mudu, S. Nickovic, D. Oyarzun, J. Prospero, G.B. Raga, A.U. Raysoni, L. Ren, N. Sarafoglou, A. Sealy, Z. Sun, and A.V. Vimic, 2023: Health and safety effects of airborne soil dust in the Americas and beyond. *Reviews of Geophysics*, **61** (2), e2021RG000763. https://doi.org/10.1029/2021rg000763

90. Twohy, C.H., S.M. Kreidenweis, T. Eidhammer, E.V. Browell, A.J. Heymsfield, A.R. Bansemer, B.E. Anderson, G. Chen, S. Ismail, P.J. DeMott, and S.C. Van Den Heever, 2009: Saharan dust particles nucleate droplets in eastern Atlantic clouds. *Geophysical Research Letters*, **36** (1). https://doi.org/10.1029/2008gl035846

91. West, J.J., A. Cohen, F. Dentener, B. Brunekreef, T. Zhu, B. Armstrong, M.L. Bell, M. Brauer, G. Carmichael, D.L. Costa, D.W. Dockery, M. Kleeman, M. Krzyzanowski, N. Künzli, C. Liousse, S.-C.C. Lung, R.V. Martin, U. Pöschl, C.A. Pope, J.M. Roberts, A.G. Russell, and C. Wiedinmyer, 2016: What we breathe impacts our health: Improving understanding of the link between air pollution and health. *Environmental Science & Technology*, **50** (10), 4895–4904. https://doi.org/10.1021/acs.est.5b03827

92. Zhang, X., L. Zhao, D.Q. Tong, G. Wu, M. Dan, and B. Teng, 2016: A systematic review of global desert dust and associated human health effects. *Atmosphere*, **7** (12), 158. https://doi.org/10.3390/atmos7120158

93. Tuttle, L.J., C. Johnson, S. Kolinski, D. Minton, and M.J. Donahue, 2020: How does sediment exposure affect corals? A systematic review protocol. *Environmental Evidence*, **9** (1), 17. https://doi.org/10.1186/s13750-020-00200-0

94. Gyan, K., W. Henry, S. Lacaille, A. Laloo, C. Lamsee-Ebanks, S. McKay, R.M. Antoine, and M.A. Monteil, 2005: African dust clouds are associated with increased paediatric asthma accident and emergency admissions on the Caribbean island of Trinidad. *International Journal of Biometeorology*, **49** (6), 371–376. https://doi.org/10.1007/s00484-005-0257-3

95. Cadelis, G., R. Tourres, and J. Molinie, 2014: Short-term effects of the particulate pollutants contained in Saharan dust on the visits of children to the emergency department due to asthmatic conditions in Guadeloupe (French archipelago of the Caribbean). *PLoS ONE*, **9** (3), e91136. https://doi.org/10.1371/journal.pone.0091136

96. Akpinar-Elci, M., F.E. Martin, J.G. Behr, and R. Diaz, 2015: Saharan dust, climate variability, and asthma in Grenada, the Caribbean. *International Journal of Biometeorology*, **59** (11), 1667–1671. https://doi.org/10.1007/s00484-015-0973-2

97. ANSES, 2017: Exposition aux Émanations des Algues Sargasses Échouées: l'Anses Réitère et Complète ses Recommandations. Agence Nationale de Sécurité Sanitaire de L'alimentation, de L'environnement et du Travail. https://www.anses.fr/fr/content/exposition-aux-%C3%A9manations-des-algues-sargasses-%C3%A9chou%C3%A9es-l%E2%80%99anses-r%C3%A9it%C3%A8re-et-compl%C3%A8te-ses

98. Fidai, Y.A., J. Dash, E.L. Tompkins, and T. Tonon, 2020: A systematic review of floating and beach landing records of Sargassum beyond the Sargasso Sea. *Environmental Research Communications*, **2** (12), 122001. https://doi.org/10.1088/2515-7620/abd109

99. Maurer, A.S., S.P. Stapleton, C.A. Layman, and M.O. Burford Reiskind, 2021: The Atlantic Sargassum invasion impedes beach access for nesting sea turtles. *Climate Change Ecology*, **2**, 100034. https://doi.org/10.1016/j.ecochg.2021.100034

100. Resiere, D., H. Mehdaoui, J. Florentin, P. Gueye, T. Lebrun, A. Blateau, J. Viguier, R. Valentino, Y. Brouste, H. Kallel, B. Megarbane, A. Cabie, R. Banydeen, and R. Neviere, 2021: Sargassum seaweed health menace in the Caribbean: Clinical characteristics of a population exposed to hydrogen sulfide during the 2018 massive stranding. *Clinical Toxicology*, **59** (3), 215–223. https://doi.org/10.1080/15563650.2020.1789162

101. Resiere, D., H. Mehdaoui, R. Névière, and B. Mégarbane, 2019: Sargassum invasion in the Caribbean: The role of medical and scientific cooperation. *Pan American Journal of Public Health*, **43**, e52. https://doi.org/10.26633/rpsp.2019.52

102. Resiere, D., R. Valentino, R. Nevière, R. Banydeen, P. Gueye, J. Florentin, A. Cabié, T. Lebrun, B. Mégarbane, G. Guerrier, and H. Mehdaoui, 2018: Sargassum seaweed on Caribbean islands: An international public health concern. *The Lancet*, **392** (10165), 2691. https://doi.org/10.1016/s0140-6736(18)32777-6

103. Rodríguez-Martínez, R.E., A.E. Medina-Valmaseda, P. Blanchon, L.V. Monroy-Velázquez, A. Almazán-Becerril, B. Delgado-Pech, L. Vásquez-Yeomans, V. Francisco, and M.C. García-Rivas, 2019: Faunal mortality associated with massive beaching and decomposition of pelagic Sargassum. *Marine Pollution Bulletin*, **146**, 201–205. https://doi.org/10.1016/j.marpolbul.2019.06.015

104. López-Sosa, L.B., J.J. Alvarado-Flores, J.C. Corral-Huacuz, A. Aguilera-Mandujano, R.E. Rodríguez-Martínez, S.J. Guevara-Martínez, J.V. Alcaraz-Vera, J.G. Rutiaga-Quiñones, J. Zárate-Medina, M.L. Ávalos-Rodríguez, and M. Morales-Máximo, 2020: A prospective study of the exploitation of pelagic Sargassum spp. as a solid biofuel energy source. *Applied Sciences*, **10** (23), 8706. https://doi.org/10.3390/app10238706

105. Tejada-Tejada, P., Y. Rodríguez-Rodríguez, L.E. Rodríguez de Francisco, O. Paino-Perdomo, and C.J. Boluda, 2021: Lead, chromium, nickel, copper and zinc levels in Sargassum species reached the coasts of the Dominican Republic during 2019: A preliminary evaluation for the use of algal biomass as fertilizer and animal feeding. *Technology And Water Sciences*, **12** (3), 124–163. https://doi.org/10.24850/j-tyca-2021-03-04

106. Thompson, T.M., B.R. Young, and S. Baroutian, 2020: Pelagic Sargassum for energy and fertiliser production in the Caribbean: A case study on Barbados. *Renewable and Sustainable Energy Reviews*, **118**, 109564. https://doi.org/10.1016/j.rser.2019.109564

107. Lloréns, H., 2021: Toxic racism in Puerto Rico's Sacrifice Zone. *NACLA Report on the Americas*, **53** (3), 275–280. https://doi.org/10.1080/10714839.2021.1961447

108. Domonoske, C., 2017: With bottles and buckets, Puerto Ricans seek the water to survive. *NPR*, September 27, 2017. https://www.npr.org/sections/thetwo-way/2017/09/27/553898689/with-bottles-and-buckets-puerto-ricans-seek-the-water-to-survive

109. Jiang, S.C., M. Han, S. Chandrasekaran, Y. Fang, and C.A. Kellogg, 2020: Assessing the water quality impacts of two Category-5 hurricanes on St. Thomas, Virgin Islands. *Water Research*, **171**, 115440. https://doi.org/10.1016/j.watres.2019.115440

110. Lin, Y., M. Sevillano-Rivera, T. Jiang, G. Li, I. Cotto, S. Vosloo, C.M.G. Carpenter, P. Larese-Casanova, R.W. Giese, D.E. Helbling, I.Y. Padilla, Z. Rosario-Pabón, C. Vélez Vega, J.F. Cordero, A.N. Alshawabkeh, A. Pinto, and A.Z. Gu, 2020: Impact of Hurricane Maria on drinking water quality in Puerto Rico. *Environmental Science & Technology*, **54** (15), 9495–9509. https://doi.org/10.1021/acs.est.0c01655

111. Schnall, A.H., J. Roth, B. Ellis, K. Seger, M. Davis, and E.M. Ellis, 2019: Addressing community needs during the hurricane response and recovery efforts through community assessments for public health emergency response (CASPER)—United States Virgin Islands, 2017–2018. *Disaster Medicine and Public Health Preparedness*, **13** (1), 53–62. https://doi.org/10.1017/dmp.2019.6

112. Cruz-Cano, R. and E.L. Mead, 2019: Causes of excess deaths in Puerto Rico after Hurricane Maria: A time-series estimation. *American Journal of Public Health*, **109** (7), 1050–1052. https://doi.org/10.2105/ajph.2019.305015

113. Marazzi, M., B. Miloucheva, and G.J. Bobon, 2021: Displacement and Mortality After a Disaster: Deaths of Puerto Ricans in the United States Post-Hurricane Maria. Working Paper 710. University of Toronto, Department of Economics. https://econpapers.repec.org/paper/tortecipa/tecipa-710.htm

114. PR DOH, 2022: Perfil Epidemiológico de la Mortalidad en Puerto Rico Años 2015–2022. Puerto Rico Department of Health. https://www.salud.pr.gov/CMS/DOWNLOAD/7323

115. Santos-Burgoa, C., A. Goldman, Andrade E., N. Barrett, U. Colon-Ramos, M. Edberg, A. Garcia-Meza, L. Goldman, A. Roess, J. Sandberg, and S. Zeger, 2018: Project Report: Ascertainment of the Estimated Excess Mortality from Hurricane María in Puerto Rico. George Washington University, Milken Institute School of Public Health. https://publichealth.gwu.edu/sites/g/files/zaxdzs4586/files/2023-06/acertainment-of-the-estimated-excess-mortality-from-hurricane-maria-in-puerto-rico.pdf

116. Barbier, E.B., 2016: The protective value of estuarine and coastal ecosystem services in a wealth accounting framework. *Environmental and Resource Economics*, **64** (1), 37–58. https://doi.org/10.1007/s10640-015-9931-z

117. Leemans, R. and R.S. de Groot, 2003: *Ecosystems and Human Well-Being: A Framework for Assessment. Millennium Ecosystem Assessment.* Island Press, Washington, DC. http://pdf.wri.org/ecosystems_human_wellbeing.pdf

118. Barreto-Orta, M., R. Méndez-Tejeda, E. Rodríguez, N. Cabrera, E. Díaz, and K. Pérez, 2019: State of the beaches in Puerto Rico after Hurricane Maria (2017). *Shore & Beach*, **87** (1). https://asbpa.org/publications/shore-and-beach/shore-beach-vol-87-no-1-winter-2019-abstracts/

119. Cox, D., T. Arikawa, A. Barbosa, G. Guannel, D. Inazu, A. Kennedy, Y. Li, N. Mori, K. Perry, D. Prevatt, D. Roueche, T. Shimozono, C. Simpson, E. Shimakawa, T. Shimura, and R. Slocum, 2019: Hurricanes Irma and Maria post-event survey in US Virgin Islands. *Coastal Engineering Journal*, **61** (2), 121–134. https://doi.org/10.1080/21664250.2018.1558920

120. Mendez-Tejeda, R., K.A. Pérez-Valentín, and M. Barreto-Orta, 2020: Impact of extreme weather events on the beaches of Puerto Rico: The case of Ocean Park, San Juan. *American Journal of Marine Science*, **8** (1), 1–5. https://doi.org/10.12691/marine-8-1-1

121. OCM, 2017: Shoreline Mileage of the United States. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. https://coast.noaa.gov/data/docs/states/shorelines.pdf

122. Gochfeld, D.J., J.B. Olson, A. Chaves-Fonnegra, T.B. Smith, R.S. Ennis, and M.E. Brandt, 2020: Impacts of Hurricanes Irma and Maria on coral reef sponge communities in St. Thomas, U.S. Virgin Islands. *Estuaries and Coasts*, **43** (5), 1235–1247. https://doi.org/10.1007/s12237-020-00694-4

123. Toledo-Hernandez, C., C. Ruiz-Diaz, E. Hernandez, and S. Suleimán-Ramos, 2018: Devastation of 15-year old community-based coral farming and reef-restoration sites in Puerto Rico by major Hurricanes Irma and María. *Caribbean Naturalist*, **53**, 1–6. https://www.eaglehill.us/CANAonline/CANA-access-pages/CANA-regular/CANA-053-Toledo-Hernandez.shtml

124. Viehman, T.S., M. Nemeth, S.H. Groves, C.A. Buckel, S. Griffin, D. Field, T.D. Moore, and J. Moore, 2020: Coral Assessment and Restoration in the U.S. Caribbean After 2017 Hurricanes. NOAA Technical Memorandum NOS NCCOS ; 278. National Oceanic and Atmospheric Administration, National Ocean Service and National Marine Fisheries Service. https://doi.org/10.25923/7r0b-wc52

125. Browning, T.N., D.E. Sawyer, G.R. Brooks, R.A. Larson, C.E. Ramos-Scharrón, and M. Canals-Silander, 2019: Widespread deposition in a coastal bay following three major 2017 hurricanes (Irma, Jose, and Maria). *Scientific Reports*, **9** (1), 7101. https://doi.org/10.1038/s41598-019-43062-4

126. Pérez Valentín, J.M. and M.F. Müller, 2020: Impact of Hurricane Maria on beach erosion in Puerto Rico: Remote sensing and causal inference. *Geophysical Research Letters*, **47** (6), e2020GL087306. https://doi.org/10.1029/2020gl087306

127. Bendik, K., A.C. Seymour, and K.S. Doran, 2021: Coastal Cliff Top and Toe Delineation Derived from Lidar for Puerto Rico: 2018. U.S. Geological Survey. https://doi.org/10.5066/f7610xcx

128. Cartier, K.M.S., 2019: Hurricanes hit Puerto Rico's mangroves harder than Florida's. *Eos*, **100**. https://doi.org/10.1029/2019eo137889

129. EPA, 2017: Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. EPA 430-R-17-001. U.S. Environmental Protection Agency, Washington, DC. https://www.epa.gov/cira/multi-model-framework-quantitative-sectoral-impacts-analysis

130. Storlazzi, C.D., B.G. Reguero, A.D. Cole, E. Lowe, J.B. Shope, A.E. Gibbs, B.A. Nickel, R.T. McCall, A.R. van Dongeren, and M.W. Beck, 2019: Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction. USGS Open-File Report 2019–1027. U.S. Geological Survey, Reston, VA, 42 pp. https://doi.org/10.3133/ofr20191027

131. USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/nca4.2018

132. Oliver, L.M., W.S. Fisher, L. Fore, A. Smith, and P. Bradley, 2018: Assessing land use, sedimentation, and water quality stressors as predictors of coral reef condition in St. Thomas, U.S. Virgin Islands. *Environmental Monitoring and Assessment*, **190**, 213. https://doi.org/10.1007/s10661-018-6562-1

133. Takesue, R.K., C. Sherman, N.I. Ramirez, A.O. Reyes, O.M. Cheriton, R.V. Ríos, and C.D. Storlazzi, 2021: Land-based sediment sources and transport to southwest Puerto Rico coral reefs after Hurricane Maria, May 2017 to June 2018. *Estuarine, Coastal and Shelf Science*, **259**, 107476. https://doi.org/10.1016/j.ecss.2021.107476

134. Smith, A., S.H. Yee, M. Russell, J. Awkerman, and W.S. Fisher, 2017: Linking ecosystem service supply to stakeholder concerns on both land and sea: An example from Guánica Bay watershed, Puerto Rico. *Ecological Indicators*, **74**, 371–383. https://doi.org/10.1016/j.ecolind.2016.11.036

135. Myers, B., 2019: Drought in the U.S. Caribbean: Impacts on Freshwater Ecosystems. U.S. Department of Agriculture, Caribbean Climate Hub, 2 pp. https://doi.org/10.32747/2019.6886313.ch

136. Gonzalez, G., E. Marín-Spiotta, and M. Matos, 2020: Appendix A: Regional summaries, Caribbean. In: *Forest and Rangeland Soils of the United States Under Changing Conditions*. Pouyat, R.V., D.S. Page-Dumroese, T. Patel-Weynand, and L. Geiser, Eds. Springer Cham, 217–229. https://doi.org/10.1007/978-3-030-45216-2

137. Mau, A.C., S.C. Reed, T.E. Wood, and M.A. Cavaleri, 2018: Temperate and tropical forest canopies are already functioning beyond their thermal thresholds for photosynthesis. *Forests*, **9** (1), 47. https://doi.org/10.3390/f9010047

138. Wood, T.E., M.A. Cavaleri, C.P. Giardina, S. Khan, J. Mohan, A.T. Nottingham, S. Reed, and M. Slot, 2019: Ch. 14. Soil warming effects on tropical forests with highly weathered soils. In: *Ecosystem Consequences of Soil Warming: Microbes, Vegetation, Fauna and Soil Biogeochemistry*. Academic Press, 385–439. https://doi.org/10.1016/b978-0-12-813493-1.00015-6

139. Wood, T.E., M. Detto, and W.L. Silver, 2013: Sensitivity of soil respiration to variability in soil moisture and temperature in a humid tropical forest. *PLoS ONE*, **8** (12), 80965. https://doi.org/10.1371/journal.pone.0080965

140. Zimmerman, J.K., T.E. Wood, G. González, A. Ramirez, W.L. Silver, M. Uriarte, M.R. Willig, R.B. Waide, and A.E. Lugo, 2021: Disturbance and resilience in the Luquillo Experimental Forest. *Biological Conservation*, **253**, 108891. https://doi.org/10.1016/j.biocon.2020.108891

141. Zimmerman, J.K., M.R. Willig, and E.A. Hernández-Delgado, 2020: Resistance, resilience, and vulnerability of social-ecological systems to hurricanes in Puerto Rico. *Ecosphere*, **11** (10), 03159. https://doi.org/10.1002/ecs2.3159

142. Fitzpatrick, S.M. and C.M. Giovas, 2021: Tropical islands of the Anthropocene: Deep histories of anthropogenic terrestrial–marine entanglement in the Pacific and Caribbean. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (40), e2022209118. https://doi.org/10.1073/pnas.2022209118

143. Coleman-Jensen, A., M.P. Rabbitt, C.A. Gregory, and A. Singh, 2016: Household Food Security in the United States in 2015. ERR-215. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=79760

144. Coleman-Jensen, A., M.P. Rabbitt, C.A. Gregory, and A. Singh, 2018: Household Food Security in the United States in 2017. ERR-256. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=90022

145. Santiago-Torres, M., E.M. Román Meléndez, I.R. Rodríguez Ayuso, and Z.L. Ríos Vázquez, 2019: Seguridad Alimentaria en Puerto Rico. Instituto de Estadísticas de Puerto Rico, 51 pp. https://estadisticas.pr/files/Comunicados/Seguridad%20Alimentaria%20en%20Puerto%20Rico%20-%20Final%20%28300519%29.pdf

146. Keith-Jennings, B. and W. Wolkomir, 2020: How Does Household Food Assistance in Puerto Rico Compare to the Rest of the United States? Center on Budget and Policy Priorities, Washington, DC, 16 pp. https://www.cbpp.org/research/food-assistance/how-does-household-food-assistance-in-puerto-rico-compare-to-the-rest-of

147. Diaz, I.I. and C. Hunsberger, 2018: Can agroecological coffee be part of a food sovereignty strategy in Puerto Rico? *Geoforum*, **97**, 84–94. https://doi.org/10.1016/j.geoforum.2018.10.016

148. Gould, W.A., S.J. Fain, I.K. Pares, K. McGinley, A. Perry, and R.F. Steele, 2015: Caribbean Regional Climate Sub Hub Assessment of Climate Change Vulnerability and Adaptation and Mitigation Strategies. U.S. Department of Agriculture, 67 pp. https://www.fs.usda.gov/detail/iitf/research/?cid=fseprd505760

149. Harmsen, E. and R.H. Harmsen, 2019: Agricultural water management and Puerto Rico's food insecurity. Special publication I 2019–2020. *Ethos Gubernamental*. https://issuu.com/eticapr/docs/ethosart_agriculturalwatermanagement_and_pr_foodin

150. Meléndez-Ayala, I. and A. Kennedy, 2021: How the U.S. dictates what Puerto Rico eats. *The New York Times*, October 1, 2021. https://www.nytimes.com/2021/10/01/opinion/puerto-rico-jones-act.html

151. Marrero, A. and J. Mattei, 2022: Reclaiming traditional, plant-based, climate-resilient food systems in small islands. *The Lancet Planetary Health*, **6** (2), e171–e179. https://doi.org/10.1016/s2542-5196(21)00322-3

152. Álvarez-Berríos, N.L., S. Soto-Bayó, E. Holupchinski, S.J. Fain, and W.A. Gould, 2018: Correlating drought conservation practices and drought vulnerability in a tropical agricultural system. *Renewable Agriculture and Food Systems*, **33** (3), 279–291. https://doi.org/10.1017/s174217051800011x

153. Statista, 2022: Puerto Rico: Distribution of Gross Domestic Product (GDP) Across Economic Sectors from 2010 to 2020 [Webpage]. https://www.statista.com/statistics/397789/puerto-rico-gdp-distribution-across-economic-sectors/

154. NASS, 2019: 2017 Census of Agriculture: United States Summary and State Data. AC-17-A-51. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/agcensus/2017/index.php

155. Ortiz-Colón, G., 2011: Impacto Sobre la Producción Agrícola y Prácticas de Adaptación: La Industria Lechera de Puerto Rico Frente al Cambio Climático. Guía Curricular del Servicio de Extensión Agrícola.

156. Ortiz-Colón, G., S.J. Fain, I.K. Parés, J. Curbelo-Rodríguez, E. Jiménez-Cabán, M. Pagán-Morales, and W.A. Gould, 2018: Assessing climate vulnerabilities and adaptive strategies for resilient beef and dairy operations in the tropics. *Climatic Change*, **146** (1), 47–58. https://doi.org/10.1007/s10584-017-2110-1

157. Iowa State University Food Systems Team, 2020: Virgin Islands Community Food Systems Snapshot. Iowa State University, 35 pp. https://www.extension.iastate.edu/ffed/wp-content/uploads/2020-Final-USVI-Snapshot_red.pdf

158. USVI Division of Economic Research, 2020: USVI's United States and Foreign Imports Annual 2019 Trade Data Report. USVI Office of Management & Budget, Division of Economic Research. https://usviber.org/wp-content/uploads/2022/07/food-imports-report-2019-2.pdf

159. NASS, 2020: Quick Stats. U.S. Department of Agriculture, National Agricultural Statistics Service. https://quickstats.nass.usda.gov/

160. NASS, 2020: 2017 Census of Agriculture—U.S. Virgin Islands Agriculture: Results from the 2018 Census of Agriculture. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/highlights/2020/census-virginislands.pdf

161. Molina-Rivera, W.L. and M.M. Irizarry-Ortiz, 2021: Estimated Water Withdrawals and Use in Puerto Rico, 2015. USGS Open-File Report 2021-1060. U.S. Geological Survey, 38 pp. https://doi.org/10.3133/ofr20211060

162. Quiñones, F., 2016: Recursos de Agua de Puerto Rico [Webpage]. https://recursosaguapuertorico.com/

163. Ramos-Gines, O., 1994: Effects of Changing Irrigation Practices on the Ground-Water Hydrology of the Santa Isabel-Juana Díaz Area, South Central Puerto Rico. Water-Resources Investigations Report 91-4183. U.S. Geological Survey, Puerto Rico, 22 pp. https://doi.org/10.3133/wri914183

164. Rodríguez, J.M., 2013: Evaluation of Groundwater Quality and Selected Hydrologic Conditions in the South Coast Aquifer, Santa Isabel Area, Puerto Rico, 2008–09. Scientific Investigations Report 2012-5254. U. S. Geological Survey, Reston, VA, 38 pp. https://doi.org/10.3133/sir20125254

165. Torres-Gonzalez, S. and J.M. Rodriguez, 2016: Hydrologic Conditions in the South Coast Aquifer, Puerto Rico, 2010–15. USGS Open-File Report 2015-1215. U.S. Geological Survey, Reston, VA, 32 pp. https://doi.org/10.3133/ofr20151215

166. Eisenhauer, D.E., D.L. Martin, D.M. Heeren, and G.J. Hoffman, 2021: *Irrigation Systems Management*, 1st ed. American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/ism.2021

167. Martinez, O., M. Muth, W.A. Gould, N.L. Álvarez-Berríos, E. Holupchinski, L.A. Rodriguez-Cruz, B. Rippey, and H.J. Jiménez, 2022: Drought Update for Puerto Rico and the U.S. Virgin Islands. National Integrated Drought Information System. https://www.drought.gov/drought-status-updates/drought-update-puerto-rico-and-us-virgin-islands-4-7-22

168. McGinley, K.A., W.A. Gould, N.L. Álvarez-Berríos, E. Holupchinski, and T. Díaz-Camacho, 2022: Ready or not? Hurricane preparedness, response, and recovery of farms, forests, and rural communities in the U.S. Caribbean. *International Journal of Disaster Risk Reduction*, **82** (2), 103346. https://doi.org/10.1016/j.ijdrr.2022.103346

169. Álvarez-Berríos, N.L., S.S. Wiener, K.A. McGinley, A.B. Lindsey, and W.A. Gould, 2021: Hurricane effects, mitigation, and preparedness in the Caribbean: Perspectives on high importance–low prevalence practices from agricultural advisors. *Journal of Emergency Management*, **19** (8), 135–155. https://doi.org/10.5055/jem.0585

170. Marrero, A., A. Lɒpez-Cepero, R. Borges-Méndez, and J. Mattei, 2022: Narrating agricultural resilience after Hurricane María: How smallholder farmers in Puerto Rico leverage self-sufficiency and collaborative agency in a climate-vulnerable food system. *Agriculture and Human Values*, **39** (2), 555–571. https://doi.org/10.1007/s10460-021-10267-1

171. Wiener, S.S., N.L. Álvarez-Berríos, and A.B. Lindsey, 2020: Opportunities and challenges for hurricane resilience on agricultural and forest land in the U.S. Southeast and Caribbean. *Sustainability*, **12** (4), 1364. https://doi.org/10.3390/su12041364

172. Herrera, D. and T. Ault, 2017: Insights from a new high-resolution drought atlas for the Caribbean spanning 1950–2016. *Journal of Climate*, **30** (19), 7801–7825. https://doi.org/10.1175/jcli-d-16-0838.1

173. Wang, R., L. Li, P. Gentine, Y. Zhang, J. Chen, X. Chen, L. Chen, L. Ning, L. Yuan, and G. Lü, 2022: Recent increase in the observation-derived land evapotranspiration due to global warming. *Environmental Research Letters*, **17** (2), 024020. https://doi.org/10.1088/1748-9326/ac4291

174. Mercado-Díaz, J.A., E. Holupchinski, N. Álvarez-Berríos, W.A. Gould, P. Miller, T. Mote, C. Ramseyer, and G. González, 2023: Fostering knowledge-exchange and collaboration among drought-related initiatives in the Caribbean. *Bulletin of the American Meteorological Society*, **104**, E1146–E1153. https://doi.org/10.1175/bams-d-23-0054.1

175. Bucheli, J., T. Dalhaus, and R. Finger, 2022: Temperature effects on crop yields in heat index insurance. *Food Policy*, **107**, 102214. https://doi.org/10.1016/j.foodpol.2021.102214

176. Tubiello, F.N., J.F. Soussana, and S.M. Howden, 2007: Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104** (50), 19686–19690. https://doi.org/10.1073/pnas.0701728104

177. Wheeler, T.R., P.Q. Craufurd, R.H. Ellis, J.R. Porter, and P.V. Vara Prasad, 2000: Temperature variability and the yield of annual crops. *Agriculture, Ecosystems & Environment*, **82** (1), 159–167. https://doi.org/10.1016/s0167-8809(00)00224-3

178. Hatfield, J.L. and J.H. Prueger, 2015: Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, **10** (Part A), 4–10. https://doi.org/10.1016/j.wace.2015.08.001

179. Gowda, P., J.L. Steiner, C. Olson, M. Boggess, T. Farrigan, and M.A. Grusak, 2018: Ch. 10. Agriculture and rural communities. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 391–437. https://doi.org/10.7930/nca4.2018.ch10

180. Ziska, L., A. Crimmins, A. Auclair, S. DeGrasse, J.F. Garofalo, A.S. Khan, I. Loladze, A.A. Pérez de León, A. Showler, J. Thurston, and I. Walls, 2016: Ch. 7. Food safety, nutrition, and distribution. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 189–216. https://doi.org/10.7930/j0zp4417

181. El Khayat, M., D.A. Halwani, L. Hneiny, I. Alameddine, M.A. Haidar, and R.R. Habib, 2022: Impacts of climate change and heat stress on farmworkers' health: A scoping review. *Frontiers in Public Health*, **10**, 782811. https://doi.org/10.3389/fpubh.2022.782811

182. Smith, M.R. and S.S. Myers, 2018: Impact of anthropogenic $CO_2$ emissions on global human nutrition. *Nature Climate Change*, **8** (9), 834–839. https://doi.org/10.1038/s41558-018-0253-3

183. Harmsen, E.W., N.L. Adames, and N.R. Maldonado, 2022: Gridded aquifer recharge estimates for the Puerto Rico south coast aquifer. In: *American Geophysical Union (AGU) 2022 Annual Meeting, Frontiers in Hydrology*. San Juan, PR, 21 June 2022. https://pragwater.com/selected-publications-and-presentations/

184. Irizarry-Ortiz, M. and E.W. Harmsen, 2023: Sensitivity of the Penman–Monteith reference evapotranspiration equation to meteorological variables for Puerto Rico. *Hydrology*, **10** (5), 101. https://doi.org/10.3390/hydrology10050101

185. Moraes, F.D.S., C. Ramseyer, and D. Gamble, 2023: The effects of projected climate change on crop water availability in the U.S. Caribbean. *Journal of Water and Climate Change*, **14** (4), 1176–1191. https://doi.org/10.2166/wcc.2023.398

186. Jhajharia, D., R. Kumar, P.P. Dabral, V.P. Singh, R.R. Choudhary, and Y. Dinpashoh, 2015: Reference evapotranspiration under changing climate over the Thar Desert in India. *Meteorological Applications*, **22** (3), 425–435. https://doi.org/10.1002/met.1471

187. Girija Veni, V., C. Srinivasarao, K. Sammi Reddy, K.L. Sharma, and A. Rai, 2020: Ch. 26. Soil health and climate change. In: *Climate Change and Soil Interactions*. Prasad, M.N.V. and M. Pietrzykowski, Eds. Elsevier, 751–767. https://doi.org/10.1016/b978-0-12-818032-7.00026-6

188. Sharma, K.L., C.S. Rao, D.S. Chandrika, M. Lal, K. Srinivas, K.S. Reddy, and A.K. Indoria, 2016: Effect of 13 years long minimum tillage cum conjunctive nutrient management practices on soil fertility and nitrogen chemical fractions under sorghum (*Sorghum bicolour* (L.) Moench)–mungbean (*Vigna radiata* (L.) Wilczek) system in semi-arid tropical Alfisol (SAT) in southern India. *Communications in Soil Science and Plant Analysis*, **47** (18), 2059–2068. https://doi.org/10.1080/00103624.2016.1225083

189. Zagal, E., C. Muñoz, M. Quiroz, and C. Córdova, 2009: Sensitivity of early indicators for evaluating quality changes in soil organic matter. *Geoderma*, **151** (3), 191–198. https://doi.org/10.1016/j.geoderma.2009.04.004

190. Chessman, D., B.N. Moebius-Clune, B.R. Smith, B. Fisher, 2019: The Basics of Addressing Resource Concerns with Conservation Practices within Integrated Management Systems on Cropland. Soil Health Technical Note No. 450-04. U.S. Department of Agriculture, Natural Resources Conservation Service. https://directives.sc.egov.usda.gov/opennonwebcontent.aspx?content=44293.wba

191. Porch, T.G., J.S. Beaver, and M.A. Brick, 2013: Registration of tepary germplasm with multiple-stress tolerance, TARS-Tep 22 and TARS-Tep 32. *Journal of Plant Registrations*, **7** (3), 358–364. https://doi.org/10.3198/jpr2012.10.0047crg

192. Cabrera, I., E.W. Harmsen, and A. Vélez, 2019: The effect of shade houses on the insect pests and yield of three important plant crops in Puerto Rico: Pepper, *Capsicum annuum* (Solanaceae), watermelon, *Citrullus lanatus* (Cucurbitaceae), and cabbage, *Brassica oleracea* (Brassicaceae). *Life: The Excitement of Biology*, **7** (1), 5–21. https://doi.org/10.9784/leb7(1)cabrera.01

193. Mathanker, S., 2021: A precision agriculture technology course for regions with lower technology adoption levels. *Applied Engineering in Agriculture*, **37** (5), 871–877. https://doi.org/10.13031/aea.14669

194. Harmsen, E.W., 2012: A simple web-based method for scheduling irrigation in Puerto Rico. *The Journal of Agriculture of the University of Puerto Rico*, **96** (3-4), 235–243. https://revistas.upr.edu/index.php/jaupr/article/view/3171/2692

195. Harmsen, E.W., 2018: Ch. 1. Simple spreadsheet method for scheduling irrigation. In: *Technological Interventions in Management of Irrigated Agriculture*. Apple Academic Press, 15. https://doi.org/10.1201/9781315204307-1

196. Mecikalski, J.R. and E.W. Harmsen, 2019: The use of visible Geostationary Operational Meteorological Satellite imagery in mapping the water balance over Puerto Rico for water resource management. In: *Satellite Information Classification and Interpretation*. Rustamov, R.B., Ed. IntechOpen. https://doi.org/10.5772/intechopen.82460

197. Mejia Manrique, S.A., E.W. Harmsen, R.M. Khanbilvardi, and J.E. González, 2021: Flood impacts on critical infrastructure in a coastal floodplain in western Puerto Rico during Hurricane María. *Hydrology*, **8** (3), 104. https://doi.org/10.3390/hydrology8030104

198. Lim, Y.-K., S.D. Schubert, R. Kovach, A.M. Molod, and S. Pawson, 2018: The roles of climate change and climate variability in the 2017 Atlantic hurricane season. *Scientific Reports*, **8** (1), 16172. https://doi.org/10.1038/s41598-018-34343-5

199. Culbertson, S., B. Nunez-Neto, J.D. Acosta, C.R. Cook, A. Lauland, K.J. Leuschner, S. Nataraj, B.L. Preston, S.A. Resetar, A.C. Resnick, P.S. Roberts, and H.J. Shatz, 2020: Recovery in the U.S. Virgin Islands: Progress, Challenges, and Options for the Future. RR-A282-1. Homeland Security Operational Analysis Center, RAND Corporation, Santa Monica, CA, 384 pp. https://doi.org/10.7249/rra282-1

200. USVI Task Force Advisory Committee, 2018: USVI Hurricane Recovery and Resilience Task Force. Government of the U.S. Virgin Islands, St. Thomas, USVI. https://cfvi.net/wp-content/uploads/2019/05/USVI_HurricaneRecoveryTaskforceReport_DIGITAL.pdf

201. Alderson, D.L., 2019: Ch. 5. Overcoming barriers to greater scientific understanding of critical infrastructure resilience. In: *Handbook on Resilience of Socio-Technical Systems*. Matthias Ruth and S. Goessling-Reisemann, Eds. Edward Elgar Publishing, 66–88. https://doi.org/10.4337/9781786439376.00010

202. Helmrich, A., S. Markolf, R. Li, T. Carvalhaes, Y. Kim, E. Bondank, M. Natarajan, N. Ahmad, and M. Chester, 2021: Centralization and decentralization for resilient infrastructure and complexity. *Environmental Research: Infrastructure and Sustainability*, **1** (2), 021001. https://doi.org/10.1088/2634-4505/ac0a4f

203. O'Neill-Carrillo, E. and M.A. Rivera-Quinones, 2018: Energy policies in Puerto Rico and their impact on the likelihood of a resilient and sustainable electric power infrastructure. *CENTRO: Journal of the Center for Puerto Rican Studies*, **30** (3), 147–171. https://go.gale.com/ps/i.do?id=GALE%7CA581024268&sid=googleScholar&v=2.1&it=r&linkaccess=abs&issn=15386279&p=AONE&sw=w

204. Puerto Rico Climate Change Council, 2013: Puerto Rico State of the Climate 2010–2013: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate. Puerto Rico Coastal Zone Management Program, Department of Natural and Environmental Resources, NOAA Office of Ocean and Coastal Resource Management, San Juan, PR. http://www.adaptationclearinghouse.org/resources/puerto-rico-state-of-the-climate-2010-2013-assessing-puerto-rico-eys-social-ecological-vulnerabilities-in-a-changing-climate.html

205. Seager, T.P., S.S. Clark, D.A. Eisenberg, J.E. Thomas, M.M. Hinrichs, R. Kofron, C.N. Jensen, L.R. McBurnett, M. Snell, and D.L. Alderson, 2017: Ch. 3. Redesigning resilient infrastructure research. In: *Resilience and Risk*. Linkov, I. and J.M. Palma-Oliveira, Eds. Springer, Dordrecht, Netherlands, 81–119. https://doi.org/10.1007/978-94-024-1123-2_3

206. Kossin, J.P., 2018: A global slowdown of tropical-cyclone translation speed. *Nature*, **558** (7708), 104–107. https://doi.org/10.1038/s41586-018-0158-3

207. Sadler, J.M., J.L. Goodall, M. Behl, B.D. Bowes, and M.M. Morsy, 2020: Exploring real-time control of stormwater systems for mitigating flood risk due to sea level rise. *Journal of Hydrology*, **583**, 124571. https://doi.org/10.1016/j.jhydrol.2020.124571

208. Shen, Y., M.M. Morsy, C. Huxley, N. Tahvildari, and J.L. Goodall, 2019: Flood risk assessment and increased resilience for coastal urban watersheds under the combined impact of storm tide and heavy rainfall. *Journal of Hydrology*, **579**, 124159. https://doi.org/10.1016/j.jhydrol.2019.124159

209. Vosper, E.L., D.M. Mitchell, and K. Emanuel, 2020: Extreme hurricane rainfall affecting the Caribbean mitigated by the Paris Agreement goals. *Environmental Research Letters*, **15**, 104053. https://doi.org/10.1088/1748-9326/ab9794

210. Guannel, G., N. Beck, J. Dwyer, J. Buchanan, G. Bove, and T. Hamlin, 2022: U.S. Virgin Island Coastal Vulnerability Index. University of the Virgin Islands, Caribbean Green Technology Center, St. Thomas, USVI, 50 pp. https://dpnr.vi.gov/wp-content/uploads/2023/05/Coastal-Vulnerability-Index-for-the-USVI.pdf

211. Campbell, J.D., M.A. Taylor, A. Bezanilla-Morlot, T.S. Stephenson, A. Centella-Artola, L.A. Clarke, and K.A. Stephenson, 2021: Generating projections for the Caribbean at 1.5, 2.0 and 2.5 °C from a high-resolution ensemble. *Atmosphere*, **12** (3), 328. https://doi.org/10.3390/atmos12030328

212. FEMA, 2021: *Effects of Saltwater Intrusion in Puerto Rico [Video]*. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://groundwateru.org/effects-of-saltwater-intrusion-in-puerto-rico/

213. USGS, 2016: Puerto Rico and the U.S. Virgin Islands regional summary. In: *Ground Water Atlas of the United States*. U.S. Geological Survey. https://pubs.usgs.gov/ha/ha730/ch_n/N-PR_VItext1.html

214. EPA, 2019: TRI Explorer: 2019 TRI Factsheet: City—Guayama, PR. U.S. Environmental Protection Agency. https://enviro.epa.gov/triexplorer/tri_factsheet.factsheet?pzip=&pstate=PR&pcity=GUAYAMA&pcounty=&pyear=%202019&pParent=TRI&pDataSet=TRIQ1

215. DRNA, 2019: Programas y Proyectos—Zona Costanera. Departamento de Recursos Naturales y Ambientales, San Juan, PR. https://www.drna.pr.gov/cat/programas-y-proyectos/zona-costanera/

216. PRDOH, 2023: CDBG-MIT Action Plan Amendment 2 (Substantial). Puerto Rico Department of Housing. https://cdbg-dr.pr.gov/en/download/cdbg-mit-action-plan-amendment-2-substantial/

217. Burillo, D., M. Chester, and B. Ruddell, 2017: Power system planning and operation across multiple coincident non-stationary temperature futures. In: *International Conference on Sustainable Infrastructure*. American Society of Civil Engineers, 293–302. https://doi.org/10.1061/9780784481196.026

218. Hughes, J., K. Cowper-Heays, E. Olesson, R. Bell, and A. Stroombergen, 2021: Impacts and implications of climate change on wastewater systems: A New Zealand perspective. *Climate Risk Management*, **31**, 100262. https://doi.org/10.1016/j.crm.2020.100262

219. Brinton, A., D.C. Diehl, T.G. Townsend, K. Deliz Quiñones, and M.M. Lichtenstein, 2022: Trees, trash, and hurricanes: The case study of Puerto Rico and vegetative disaster debris management after Hurricanes Irma and Maria. *International Journal of Disaster Risk Reduction*, **82**, 103298. https://doi.org/10.1016/j.ijdrr.2022.103298

220. Brown, C., M. Milke, and E. Seville, 2011: Disaster waste management: A review article. *Waste Management*, **31** (6), 1085–1098. https://doi.org/10.1016/j.wasman.2011.01.027

221. Romanello, M., A. McGushin, C. Di Napoli, P. Drummond, N. Hughes, L. Jamart, H. Kennard, P. Lampard, B. Solano Rodriguez, N. Arnell, S. Ayeb-Karlsson, K. Belesova, W. Cai, D. Campbell-Lendrum, S. Capstick, J. Chambers, L. Chu, L. Ciampi, C. Dalin, N. Dasandi, S. Dasgupta, M. Davies, P. Dominguez-Salas, R. Dubrow, K.L. Ebi, M. Eckelman, P. Ekins, L.E. Escobar, L. Georgeson, D. Grace, H. Graham, S.H. Gunther, S. Hartinger, K. He, C. Heaviside, J. Hess, S.-C. Hsu, S. Jankin, M.P. Jimenez, I. Kelman, G. Kiesewetter, P.L. Kinney, T. Kjellstrom, D. Kniveton, J.K.W. Lee, B. Lemke, Y. Liu, Z. Liu, M. Lott, R. Lowe, J. Martinez-Urtaza, M. Maslin, L. McAllister, C. McMichael, Z. Mi, J. Milner, K. Minor, N. Mohajeri, M. Moradi-Lakeh, K. Morrissey, S. Munzert, K.A. Murray, T. Neville, M. Nilsson, N. Obradovich, M.O. Sewe, T. Oreszczyn, M. Otto, F. Owfi, O. Pearman, D. Pencheon, M. Rabbaniha, E. Robinson, J. Rocklöv, R.N. Salas, J.C. Semenza, J. Sherman, L. Shi, M. Springmann, M. Tabatabaei, J. Taylor, J. Trinanes, J. Shumake-Guillemot, B. Vu, F. Wagner, P. Wilkinson, M. Winning, M. Yglesias, S. Zhang, P. Gong, H. Montgomery, A. Costello, and I. Hamilton, 2021: The 2021 report of the Lancet Countdown on health and climate change: Code red for a healthy future. *The Lancet*, **398** (10311), 1619–1662. https://doi.org/10.1016/s0140-6736(21)01787-6

222. Ferrario, F., M.W. Beck, C.D. Storlazzi, F. Micheli, C.C. Shepard, and L. Airoldi, 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, **5** (1), 3794. https://doi.org/10.1038/ncomms4794

223. Lewsey, C., G. Cid, and E. Kruse, 2004: Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean. *Marine Policy*, **28** (5), 393–409. https://doi.org/10.1016/j.marpol.2003.10.016

224. Narayan, S., M.W. Beck, B.G. Reguero, I.J. Losada, B. van Wesenbeeck, N. Pontee, J.N. Sanchirico, J.C. Ingram, G.-M. Lange, and K.A. Burks-Copes, 2016: The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS ONE*, **11** (5), e0154735. https://doi.org/10.1371/journal.pone.0154735

225. Tomiczek, T., A. Wargula, N.R. Hurst, D.B. Bryant, and L.A. Provost, 2021: Engineering with Nature: The Role of Mangroves in Coastal Protection. ERDC/TN EWN-21-1. U.S. Army Corps of Engineers, Engineer Research and Development Center, 19 pp. https://doi.org/10.21079/11681/42420

226. Djakouré, S., M. Araujo, A. Hounsou-Gbo, C. Noriega, and B. Bourlès, 2017: On the potential causes of the recent Pelagic Sargassum blooms events in the tropical North Atlantic Ocean. *Biogeosciences Discussions*, 1–20. https://doi.org/10.5194/bg-2017-346

227. *Oversight Hearing on the Puerto Rico Electric Power Authority (Prepa) Postimplementation of the Luma Transmission and Distribution Contract, U.S. House of Representatives, Committee on Natural Resources*, 2021: United States Congress, One Hundred Seventeenth, First Session. https://www.congress.gov/event/117th-congress/house-event/114107

228. UNEP-CEP, 2021: Sargassum white paper–turning the crisis into an opportunity. In: *Ninth Meeting of the Scientific and Technical Advisory Committee (STAC) to the Protocol Concerning Specially Protected Areas and Wildlife (SPAW) in the Wider Caribbean Region*. Kingston, Jamaica. United Nations Environment Programme-Caribbean Environment Programme. https://www.unep.org/cep/resources/publication/sargassum-white-paper-turning-crisis-opportunity

229. USVI Office of the Governor, 2022: Executive Order No. 525-2022: Order and Proclamation by the Governor of the United States Virgin Islands Declaring State of Emergency in the United States Virgin Islands Due to Unprecedented Influx of Sargassum Seaweed Affecting the Territory Water Supply. U.S. Virgin Islands, Office of the Governor, Charlotte Amalie, VI. https://www.vi.gov/wp-content/uploads/2022/07/exo-523-2022-state-of-emergency-sargassum-2022-07.22.pdf

230. Fischbach, J.R., L. Warren May, K. Whipkey, S.R. Shelton, C.A. Vaughan, D. Tierney, K.J. Leuschner, L.S. Meredith, and H.J. Peterson, 2020: *After Hurricane Maria: Predisaster Conditions, Hurricane Damage, and Recovery Needs in Puerto Rico*. RAND Corporation, Santa Monica, CA. https://doi.org/10.7249/rr2595

231. Joseph, S.R., C. Voyles, K.D. Williams, E. Smith, and M. Chilton, 2020: Colonial neglect and the right to health in Puerto Rico after Hurricane Maria. *American Journal of Public Health*, **110** (10), 1512–1518. https://doi.org/10.2105/ajph.2020.305814

232. Park, J., T.P. Seager, P.S.C. Rao, M. Convertino, and I. Linkov, 2013: Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis*, **33** (3), 356–367. https://doi.org/10.1111/j.1539-6924.2012.01885.x

233. Woods, D.D., 2015: Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering & System Safety*, **141**, 5–9. https://doi.org/10.1016/j.ress.2015.03.018

234. Blondeau, J., M. Brandt, C. Donovan, M. Eakin, K. Edwards, K. Edwards, P. Edwards, I. Enochs, M. Feeley, C. Fleming, N. Formel, E. Geiger, M. Gorstein, J. Grove, S. Groves, L. Henderson, M. Hibbert, N. Holloway, M. Johnson, T. Kelley, H. Kelsey, J. Koss, D. Manzello, N. Miller, C. Pott, T. Smith, E. Towle, and S. Viehman, 2020: Coral Reef Condition: A Status Report for the U.S. Virgin Islands. National Oceanic Atmospheric Administration, Coral Reef Conservation Program. https://doi.org/10.25923/53gr-cn06

235. Roth, K., 2019: U.S. Climate Resilience Toolkit: Aquifer Storage and Recovery: A Strategy for Long-Term Water Security in Puerto Rico. U.S. Global Change Research Program. https://toolkit.climate.gov/case-studies/aquifer-storage-and-recovery-strategy-long-term-water-security-puerto-rico

236. Soanes, L.M., S. Pike, S. Armstrong, K. Creque, R. Norris-Gumbs, S. Zaluski, and K. Medcalf, 2021: Reducing the vulnerability of coastal communities in the Caribbean through sustainable mangrove management. *Ocean & Coastal Management*, **210**, 105702. https://doi.org/10.1016/j.ocecoaman.2021.105702

237. Akpinar Ferrand, E. and F. Cecunjanin, 2014: Potential of rainwater harvesting in a thirsty world: A survey of ancient and traditional rainwater harvesting applications. *Geography Compass*, **8** (6), 395–413. https://doi.org/10.1111/gec3.12135

238. Silva, A., M. Rosano, L. Stocker, and L. Gorissen, 2017: From waste to sustainable materials management: Three case studies of the transition journey. *Waste Management*, **61**, 547–557. https://doi.org/10.1016/j.wasman.2016.11.038

239. NASA, 2022: Responding to Climate Change. National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology. https://climate.nasa.gov/solutions/adaptation-mitigation/

240. Pauliuk, S., N. Heeren, P. Berrill, T. Fishman, A. Nistad, Q. Tu, P. Wolfram, and E.G. Hertwich, 2021: Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nature Communications*, **12** (1), 5097. https://doi.org/10.1038/s41467-021-25300-4

241. Rothausen, S.G.S.A. and D. Conway, 2011: Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, **1** (4), 210–219. https://doi.org/10.1038/nclimate1147

242. Surana, K. and S.M. Jordaan, 2019: The climate mitigation opportunity behind global power transmission and distribution. *Nature Climate Change*, **9** (9), 660–665. https://doi.org/10.1038/s41558-019-0544-3

243. EPA, 2021: Power Plants and Neighboring Communities. U.S. Environmental Protection Agency. https://www.epa.gov/airmarkets/power-plants-and-neighboring-communities

244. Darghouth, N.R., E. O'Shaughnessy, S. Forrester, and G. Barbose, 2022: Characterizing local rooftop solar adoption inequity in the US. *Environmental Research Letters*, **17** (3), 034028. https://doi.org/10.1088/1748-9326/ac4fdc

245. Goldstein, B., T.G. Reames, and J.P. Newell, 2022: Racial inequity in household energy efficiency and carbon emissions in the United States: An emissions paradox. *Energy Research & Social Science*, **84**, 102365. https://doi.org/10.1016/j.erss.2021.102365

246. Adeh, E.H., S.P. Good, M. Calaf, and C.W. Higgins, 2019: Solar PV power potential is greatest over croplands. *Scientific Reports*, **9** (1), 11442. https://doi.org/10.1038/s41598-019-47803-3

247. Beller, W.S., P.G. D'Ayala, and P. Hein, 1990: Sustainable development and environmental management of small islands. In: *Man and the Biosphere Series*. UNESCO, 419. https://portals.iucn.org/library/taxonomy/term/36861

248. Robinson, S.-A., 2020: Climate change adaptation in SIDS: A systematic review of the literature pre and post the IPCC Fifth Assessment Report. *WIREs Climate Change*, **11** (4), e653. https://doi.org/10.1002/wcc.653

249. Jacobs, K.R., S.J. Fain, S. Henry, W. Archibald, and W.A. Gould, 2016: Synthesis of Climate Change Related Knowledge and Information in the United States Virgin Islands: An Institutional Analysis. Report for the U.S. Department of Interior, Office of Insular Affairs. U.S. Department of Agriculture, Caribbean Climate Hub, U.S. Forest Service, International Institute of Tropical Forestry, 177 pp. https://www.fs.usda.gov/detail/iitf/research/?cid=fseprd707155

250. Keenan, J.M. and M.E. Hauer, 2020: Resilience for whom? Demographic change and the redevelopment of the built environment in Puerto Rico. *Environmental Research Letters*, **15** (7), 074028. https://doi.org/10.1088/1748-9326/ab92c2

251. OCM, 2018: Final Evaluation Findings: U.S. Virgin Islands Coastal Management Program. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. https://coast.noaa.gov/data/czm/media/usvi-cmp.pdf

252. Alderson, D.L., B.B. Bunn, D.A. Eisenberg, A.R. Howard, D.A. Nussbaum, and J. Templeton II, 2018: Interdependent Infrastructure Resilience in the U.S. Virgin Islands: Preliminary Assessment. NPS-OR-18-005. Naval Postgraduate School, Monterey, CA, 128 pp. https://faculty.nps.edu/dlalders/usvi/nps-or-18-005.pdf

253. Nunez-Neto, B., A. Lauland, J. Aguirre, G. Castro, I.A. Gutierrez, M. Lara, E. Rosas, and B.A. Weidmer, 2020: Municipalities on the Front Lines of Puerto Rico's Recovery: Assessing Damage, Needs, and Opportunities for Recovery After Hurricane Maria. RR-2604-DHS. RAND Corporation, Santa Monica, CA, 216 pp. https://doi.org/10.7249/rr2604

254. Santiago, L., M. Barreto, A. Montañez-Acuña, T. Flecha, N. Cabrera, V. Bonano, L.B. Marrero, and E. Díaz, 2021: A coastal vulnerability framework to guide natural infrastructure funds allocation in compressed time. *Environmental Management*, **67** (1), 67–80. https://doi.org/10.1007/s00267-020-01397-z

255. Puerto Rico Climate Change Mitigation, Adaptation, and Resilience Act. No. 33-2019, Government of Puerto Rico, May 22, 2019. https://bvirtualogp.pr.gov/ogp/Bvirtual/leyesreferencia/PDF/2-ingles/0033-2019.pdf

256. USVI Office of the Governor, 2015: Executive Order No. 474-2015: Preparing the Virgin Islands of the United States for Adapting to the Impacts of Climate Change. U.S. Virgin Islands, Office of the Governor, Charlotte Amalie, VI. https://www.fdpi.org/wp-content/uploads/2016/01/USVI-Climate-Change-Executive-Order_474-2015.pdf

257. Engelman, A., M.T. Guzzardo, M. Antolin Muñiz, L. Arenas, and A. Gomez, 2022: Assessing the emergency response role of community-based organizations (CBOs) serving people with disabilities and older adults in Puerto Rico post-Hurricane María and during the COVID-19 pandemic. *International Journal of Environmental Research and Public Health*, **19** (4), 2156. https://doi.org/10.3390/ijerph19042156

258. Filantropía Puerto Rico, 2022: Estudio Sobre el Impacto Económico y Social de las Organizaciones sin Fines de Lucro en Puerto Rico, 2022. Filantropía Puerto Rico, Inc. https://filantropiapr.org/estudio-sobre-el-impacto-economico-y-social-de-las-organizaciones-sin-fines-de-lucro-en-puerto-rico-2022/

259. Rivas, M., 2018: La respuesta al desastre y las organizaciones sin fines de lucro en Puerto Rico. *Revista De Administración Pública*, **49**, 39–65. https://revistas.upr.edu/index.php/ap/article/view/13778

260. Roque, A.D., D. Pijawka, and A. Wutich, 2020: The role of social capital in resiliency: Disaster recovery in Puerto Rico. *Risk, Hazards & Crisis in Public Policy*, **11** (2), 204–235. https://doi.org/10.1002/rhc3.12187

261. McKayle, C., G. Guannel, M. Taylor, and T. Stephenson, 2019: Climate Change Adaptation Planning Assessment and Implementation: Final Vulnerability and Risk Assessment Report. University of the Virgin Islands and University of the West Indies, Mona. https://www.doi.gov/sites/doi.gov/files/1.-usvi-climate-vulnerability-and-risk-assessment-report-final.pdf

262. Towe, V.L., E.L.P. Sayers, E.W. Chan, A.Y. Kim, A. Tom, W.Y. Chan, J.P. Marquis, M.W. Robbins, L. Saum-Manning, M.M. Weden, and L.A. Payne, 2020: Community Planning and Capacity Building in Puerto Rico After Hurricane Maria: Predisaster Conditions, Hurricane Damage, and Courses of Action. RAND Corporation, Homeland Security Operational Analysis Center. https://doi.org/10.7249/rr2598

263. Rudge, K., 2021: Changing climate, changing discourse: Analyzing reporting of climate change and economic development in the U.S. Virgin Islands. *Climate Risk Management*, **33**, 100350. https://doi.org/10.1016/j.crm.2021.100350

264. Díaz-García, R., M. Feliciano, A. Cases, and K. Ruiz-Serrano, 2021: Adulto Mayor 2019. División de Prevención y Control de Enfermedades Crónicas, Secretaría de Promoción para la Salud del Departamento de Salud de Puerto Rico. https://www.salud.pr.gov/CMS/DOWNLOAD/5543

265. Instituto del Desarrollo de la Juventud, 2021: Perfil de Niños, Niñas y Jóvenes Viviendo en Pobreza en Puerto Rico: 2021. Instituto del Desarrollo de la Juventud. https://assets.website-files.com/60f311e9e2e57d2e3028bb6f/615fab750b18ba319f0e9ed3_perfiledejovenesviviendoenpobreza.pdf

266. Lafarga Previdi, I. and C.M. Vélez Vega, 2020: Health Disparities Research Framework adaptation to reflect Puerto Rico's socio-cultural context. *International Journal of Environmental Research and Public Health*, **17** (22), 8544. https://doi.org/10.3390/ijerph17228544

267. Farber, D.A., 2018: Response and Recovery After Maria: Lessons for Disaster Law and Policy. UC Berkeley Public Law Research Paper. University of California, Berkeley. https://doi.org/10.2139/ssrn.3174466

268. Ma, C., A.C. Baker, and T.E. Smith, 2021: How income inequality influenced personal decisions on disaster preparedness: A multilevel analysis of homeowners insurance among Hurricane Maria victims in Puerto Rico. *International Journal of Disaster Risk Reduction*, **53**, 101953. https://doi.org/10.1016/j.ijdrr.2020.101953

269. Eckstein, D., V. Künzel, and L. Schäfer, 2021: *Who suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2019 and 2000 to 2019. Global Climate Risk Index 2021.* Germanwatch, Berlin, Germany. https://www.germanwatch.org/en/19777

270. Migration Data Portal, 2021: Migration Data in the Caribbean. Global Migration Data Portal. https://www.migrationdataportal.org/regional-data-overview/migration-data-caribbean

271. Piguet, E., 2022: Linking climate change, environmental degradation, and migration: An update after 10 years. *WIREs Climate Change*, **13** (1), 746. https://doi.org/10.1002/wcc.746

272. Arrieta, A., S. Chen, J. Sarmiento, and R. Olson, 2021: Real-Time Migration Tracking to Puerto Rico after Natural Hazard Events. Natural Hazards Center Public Health Report Series, 4. University of Colorado Boulder, Natural Hazards Center, Boulder, CO. https://hazards.colorado.edu/public-health-disaster-research/real-time-migration-tracking-to-puerto-rico-after-natural-hazard-events

273. Chandrasekhar, D., I. García, and S. Khajehei, 2022: Recovery capacity of small nonprofits in post-2017 hurricane Puerto Rico. *Journal of the American Planning Association*, **88** (2), 206–219. https://doi.org/10.1080/01944363.2021.1938637

274. Rosas, E., P.S. Roberts, A. Lauland, I.A. Gutierrez, and B. Nuñez-Neto, 2021: Assessing the impact of municipal government capacity on recovery from Hurricane Maria in Puerto Rico. *International Journal of Disaster Risk Reduction*, **61**, 102340. https://doi.org/10.1016/j.ijdrr.2021.102340

275. CRS, 2021: FEMA Pre-Disaster Mitigation: The Building Resilient Infrastructure and Communities (BRIC) Program. CRS Report IN11515. Congressional Research Service. https://crsreports.congress.gov/product/pdf/in/in11515

276. GAO, 2019: Emergency Management: FEMA Has Made Progress, but Challenges and Future Risks Highlight Imperative for Further Improvements. GAO-19-617T. U.S. Government Accountability Office. https://www.gao.gov/products/gao-19-617t

277. GAO, 2022: Update on FEMA's Disaster Recovery Efforts in Puerto Rico and the U.S. Virgin Islands. GAO-22-106211. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-22-106211.pdf

278. Global Infrastructure Hub, 2022: A G20 Initiative: Lastest from the GI Hub. Global Infrastructure Hub. https://www.gihub.org/

279. Governors' Institute on Community Design, 2017: Final Report: Sea Level Rise and the Impact on Economic Activity in Coastal Communities—A Workshop for the U.S. Virgin Islands. Governors' Institute on Community Design, 34 pp. https://www.fdpi.org/wp-content/uploads/2022/07/Report-of-Workshop-on-the-Impact-of-Sea-Level-Rise-on-the-U.S.-Virgin-Islands_GICD-2017.pdf

280. Kuhl, L., 2021: Policy making under scarcity: Reflections for designing socially just climate adaptation policy. *One Earth*, **4** (2), 202–212. https://doi.org/10.1016/j.oneear.2021.01.008

281. Pitter, J., 2021: Equitable Infrastructure: A Resource Framing Infrastructure Types Using an Equitable Placemaking Lens. Community Foundations of Canada, 24 pp. https://torontolip.com/resources/resource/equitable-infrastructure-a-resource-framing-infrastructure-types-using-an-equitable-placemaking-lens/

282. Office of the High Commissioner for Human Rights, 2022: Annual Report of the United Nations High Commissioner for Human Rights on the Situation of Human Rights in Nicaragua. United Nations. https://www.ohchr.org/en/statements/2022/03/annual-report-united-nations-high-commissioner-human-rights-situation-human

283. Multihazard Mitigation Council, 2017: Natural Hazard Mitigation Saves 2017 Interim Report: An Independent Study–Summary of Findings. Principal Investigator Porter, K.; co-Principal Investigators Scawthorn, C.; Dash, N.; Santos, J.; P. Schneider, Director, MMC. National Institute of Building Sciences, Washington, DC. https://www.fema.gov/sites/default/files/2020-07/fema_ms2_interim_report_2017.pdf

284. UNDRR, 2016: UNISDR Annual Report 2015. United Nations Office for Disaster Risk Reduction, Geneva, Switzerland, 75 pp. https://www.undrr.org/publication/unisdr-annual-report-2015

285. VIHFA, 2021: United States Virgin Islands CDBG-Mitigation Action Plan. Virgin Islands Housing Finance Authority. https://cdbgdr.vihfa.gov/wp-content/uploads/2023/08/USVI-HUD-Approved-Mitgation-Action-Plan-7142021-compressed.pdf

286. Kompaniyets, L., A.B. Goodman, B. Belay, D.S. Freedman, M.S. Sucosky, S.J. Lange, A.V. Gundlapalli, T.K. Boehmer, and H.M. Blanck, 2021: Body mass index and risk for COVID-19–related hospitalization, intensive care unit admission, invasive mechanical ventilation, and death—United States, March–December 2020. *Morbidity and Mortality Weekly Report*, **70**, 355–361. https://doi.org/10.15585/mmwr.mm7010e4

287. Maldonado, J., I.F.C. Wang, F. Eningowuk, L. Iaukea, A. Lascurain, H. Lazrus, C.A. Naquin, J.R. Naquin, K.M. Nogueras-Vidal, K. Peterson, I. Rivera-Collazo, M.K. Souza, M. Stege, and B. Thomas, 2021: Addressing the challenges of climate-driven community-led resettlement and site expansion: Knowledge sharing, storytelling, healing, and collaborative coalition building. *Journal of Environmental Studies and Sciences*, **11** (3), 294–304. https://doi.org/10.1007/s13412-021-00695-0

288. Seara, T., R. Pollnac, and K. Jakubowski, 2020: Impacts of natural disasters on subjective vulnerability to climate change: A study of Puerto Rican fishers' perceptions after Hurricanes Irma & Maria. *Coastal Management*, **48** (5), 418–435. https://doi.org/10.1080/08920753.2020.1795969

289. Dawson, T., 2013: Erosion and coastal archaeology: Evaluating the threat and prioritising action. In: *Ancient Maritime Communities and the Relationship between People and Environment along the European Atlantic Coasts*. Daire, M.-Y., C. Dupont, A. Baudry, C. Billard, J.-M. Large, L. Lespez, E. Normand, and C. Scarre, Eds. Archeopress, Oxford, UK, 77–83. http://hdl.handle.net/10023/4183

290. Finneran, N.P., 2017: The materiality of human–water interaction in the Caribbean: An archaeological perspective. *WIREs Water*, **4** (5), e1235. https://doi.org/10.1002/wat2.1235

291. Kohler, T.A. and M. Rockman, 2020: The IPCC: A primer for archaeologists. *American Antiquity*, **85** (4), 627–651. https://doi.org/10.1017/aaq.2020.68

292. Perdikaris, S., R. Boger, E. Gonzalez, E. Ibrahimpašić, and J.D. Adams, 2021: Disrupted identities and forced nomads: A post-disaster legacy of neocolonialism in the island of Barbuda, Lesser Antilles. *Island Studies Journal*, **16** (1), 115–134. https://doi.org/10.24043/isj.130

293. Rockman, M. and C. Hritz, 2020: Expanding use of archaeology in climate change response by changing its social environment. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (15), 8295–8302. https://doi.org/10.1073/pnas.1914213117

294. NCHS, 2019: Potentially Excess Deaths. Centers for Disease Control and Prevention, National Center for Health Statistics, accessed April 3, 2023. https://www.cdc.gov/nchs/nvss/potentially_excess_deaths.htm

295. d'Alpoim Guedes, J., S. Gonzalez, and I. Rivera-Collazo, 2021: Resistance and care in the time of COVID-19: Archaeology in 2020. *American Anthropologist*, **123** (4), 898–915. https://doi.org/10.1111/aman.13669

296. Isabel Rivera-Collazo (Author), March 2021: Oral communications with multiple elders of Puerto Rican towns, Jayuya, Utuado, and Lajas.

297. Veenema, T.G., Z. Rush, K. Depriest, and L. Mccauley, 2019: Climate change-related hurricane impact on Puerto Rico and the US Virgin Islands, environment risk reduction, and the social determinants of health. *Nursing Economics*, **37** (1), 13–22. https://tools.niehs.nih.gov/cchhl/index.cfm/detail/18106

298. Main, J., M.K. Dillard, E.D. Kuligowski, B. Davis, J.D. Dukes, K.W. Harrison, J. Helgeson, K.J. Johnson, M.L. Levitan, J. Mitrani-Reiser, S.J. Weaver, D. Yeo, L.D. Bermúdez, J. Cline, and T. Kirsch, 2021: Learning from Hurricane Maria's Impacts on Puerto Rico: A Progress Report. NIST Special Publication 1262. National Institute of Standards and Technology. https://doi.org/10.6028/nist.sp.1262

299. Pasch, R.J., A.B. Penny, and R. Berg, 2023: Tropical Cyclone Report: Hurricane Maria. National Oceanic and Atmospheric Administration, National Weather Service, National Hurricane Center, 48 pp. https://issuu.com/coleccionpuertorriquena/docs/al152017_maria

300. DRNA, 2016: Informe Sobre la Sequía de 2014–2016 en Puerto Rico. Departamento De Recursos Naturales Y Ambientales, División Monitoreo del Plan de Aguas, San Juan, PR. https://www.drna.pr.gov/wp-content/uploads/2017/01/Informe-Sequia-2014-2016.compressed.pdf

301. NIDIS, 2023: Drought Status Update Repository. National Integrated Drought Information System and National Oceanic and Atmospheric Administration. https://www.drought.gov/drought-status-updates

302. Rodriguez-Cruz, L.A. 2022: Adaptive Capacity and [un]Natural Disasters: Puerto Rican Farmers' Adaption and Food Security Outcomes After Hurricane Maria. Doctor of Philosophy in Food Systems, University of Vermont. https://scholarworks.uvm.edu/graddis/1509

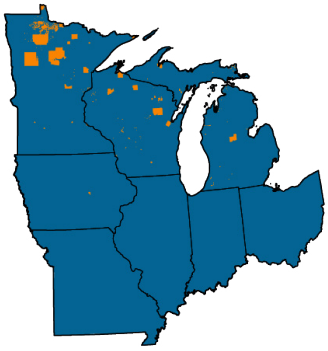
303. Environmental Defense Fund, 2021: Climate Change-Resilient Fisheries in the Caribbean–Focus on Cuba, the Dominican Republic and Puerto Rico: Summary. Environmental Defense Fund. https://www.edf.org/sites/default/files/2022-06/Caribbean%20Climate%20Resilient%20Fisheries%20Seminar%20Report_ENGLISH.pdf

304. Global Programme on Risk Assessment and Management for Adaptation to Climate Change, 2021: Climate Change and Small-Scale Fisheries: A Climate Risk Management Perspective for the Caribbean. Deutsche Gesellschaft für Internationale Zusammenarbeit, Bonn, Germany, 9 pp. https://www.adaptationcommunity.net/publications/climate-change-and-small-scale-fisheries-a-climate-risk-management-perspective-for-the-caribbean/

305. Yandle, T., J. Sweeney Tookes, and C.A. Grace-McCaskey, 2020: US Virgin Islands fishing community resilience: Informing a research agenda. *Coastal Management*, **48** (5), 481–504. https://doi.org/10.1080/08920753.2020.1796191

Fifth National Climate Assessment: Chapter 24

# Midwest



# Chapter 24. Midwest

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# Introduction

The Midwest is diverse in landscapes, people, and culture. The region covers more than 328 million acres, with approximately 284 million acres covered by croplands and forests or designated as public land. It sustains vital ecosystems and wildlife and provides refuge and recreation for its residents, including 35 Federally Recognized Tribes and numerous other state-recognized and non-recognized Tribes. More than 40,000 natural lakes and thousands more human-made reservoirs and ponds dot the landscape. The Midwest borders four of the five Great Lakes; together, the five Great Lakes contain approximately 21% of the world's surface freshwater supply, and about 10% of the US population lives within the Great Lakes basin. There are more than 500,000 miles of rivers and streams flowing through the region, including the Mississippi, Missouri, and Ohio Rivers—critical lifelines enabling the exchange of goods and services throughout the country. The Midwest is linked by more than 2 million miles of roads, 160,000 bridges, 34,000 rail miles, and 3,000 airports. It has 41 cities with at least 100,000 residents, including 5 of the 30 most populated cities in the United States. All of the Midwest states except Illinois have lower urban populations than the national average, and 74.3% of the Midwest population lives in urban areas.[1]

The climate of the Midwest has warmed since the first half of the 20th century, and annual precipitation has increased (Figure 2.4). Sub-annual changes, such as the recent lack of warming during summer and rapid oscillations between extreme wet and dry periods (Figure 24.1), increase the complexity and uncertainty of future impacts. Nonetheless, these changes have impacted agriculture (KM 24.1), natural resources (KM 24.2), health and well-being (KM 24.3), the built environment and transportation (KM 24.4), and water quality and quantity (KM 24.5) in societally important and interconnected ways. Increasing temperatures and oscillations between extreme droughts and floods threaten field crops, specialty crops, and animal production across the Midwest,[2,3] which have direct and inequitable impacts on global food supply and security (KM 11.2). These rapid oscillations in hydrology will continue to transform aquatic and terrestrial ecosystems, many of which strongly influence individual and community health and the built environment. These observed and projected changes greatly limit access to natural areas, including those intimately tied to winter ice.[4] Not only does climate change threaten recreation and the economy of this region, but it also disrupts important identity connections between Indigenous Peoples and their ancestral lands (KM 16.1).[5] Individual and community health is at risk, with cascading impacts on social and cultural connections that highlight inequitable health disparities tied to race, ethnicity, age, and income (KMs 14.1, 15.2). Aging infrastructure creates uncertainty in the ability to meet current and future energy needs and withstand increasing volumes of water. Although rural landscapes dominate the Midwest, urban centers concentrate climate risks and socioeconomic inequities (KM 12.2). NOAA's Billion-Dollar Weather and Climate Disasters report (Figure 2.6) does not fully account for the burden felt by low-income populations of urban centers due to chronic, smaller-scale flooding events. Finally, projected increases in temperature and precipitation variability threaten the ability to maintain water quality and manage the Mississippi, Missouri, and Ohio Rivers in ways that maintain the flow of goods and services throughout the region and the country. The Great Lakes indicators, from fish consumption to invasive species, show diverse conditions. Many of the complex interactions between climate changes, the lakes, and their surrounding land and populations raise uncertainty in long-term projections of lake levels and trends in environmental and ecosystem metrics (Table 24.1),[6] and this uncertainty has important implications for international collaboration and adaptive management in the Great Lakes (Box 4.3).

Despite these many risks to the economy and identity of the Midwest, people are responding in ways that offer hope for the future. Researchers are identifying climate-smart agriculture practices that could help boost profitability and improve economic and environmental sustainability (Figure 24.4). There is growing recognition that undeveloped natural lands provide economic and social benefits by contributing to climate mitigation and adaptation (providing nature-based solutions through effective resource management)

and that collaboration with Tribes on land issues improves climate outcomes for all residents. Within communities, people are engaging with one another to identify solutions to address structural, institutional, and systemic factors that contribute to inequities and climate injustice. Researchers and practitioners are collaborating to build transportation and energy networks that are resilient to climate change while also maintaining social cohesion in the process. For example, experimental port management in the Great Lakes is assuming the role of ecological restoration, which also improves the social health of the region (Figure 24.9). Communities like Milwaukee have developed public–private partnerships and increased green stormwater infrastructure. Finally, federal partners are working with state and local agencies to build tools and approaches to address climate-related challenges such as drought and harmful algal blooms.

## Key Message 24.1

## Climate-Smart Practices May Offset Complex Climate Interactions in Agriculture

Crop production is projected to change in complex ways (*likely*, *medium confidence*) due to increasing extreme precipitation events and transitions between wet and dry conditions (*likely*, *medium confidence*), as well as intensification of crop water loss (*likely*, *low confidence*). Changes in precipitation extremes, timing of snowmelt, and early-spring rainfall are expected to pose greater challenges for crop and animal agriculture, including increased pest and disease transmission, muddier pastures, and further degradation of water quality (*likely*, *high confidence*). Climate-smart agriculture and other adaptation techniques provide a potential path toward environmental and economic sustainability (*medium confidence*).

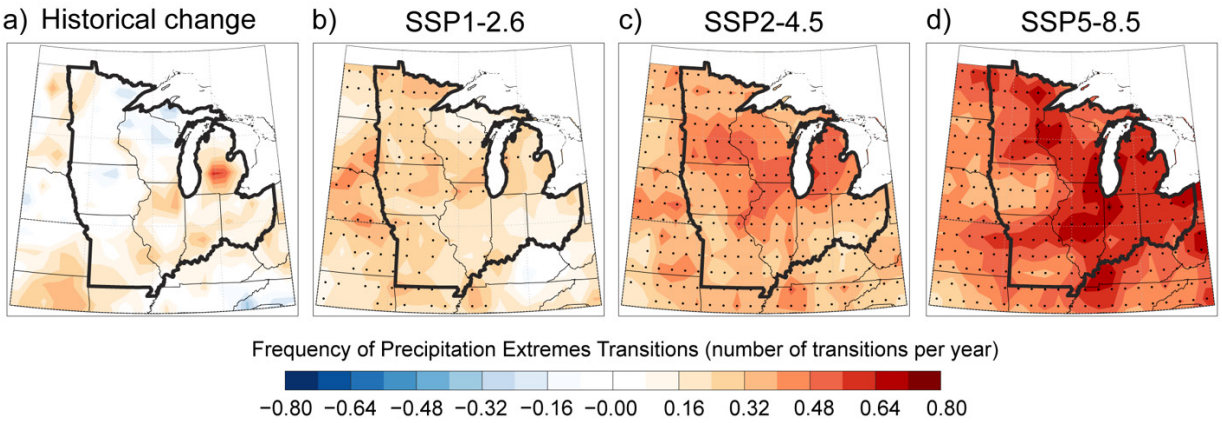
### *Risk*

The Midwest is among the most intensive agricultural regions globally, producing more than 30% and 32% of the world's corn and soybeans, respectively; numerous specialty crops; and livestock in concentrated animal operations.[7,8] Climate change is already affecting Midwest agriculture, and projected climate changes increase these risks.

### *Impacts*

Annual precipitation increased by 5%–15% across much of the Midwest during 1992–2021 (compared to the 1901–1960 average), with some areas experiencing reduced precipitation during summer (Figure 2.4).[9,10,11,12] These trends, particularly across the north-central region of the US, have been partly attributable to human influence.[13,14] Projections (under low [RCP2.6] to very high [RCP8.5] scenarios) suggest precipitation increases across the Midwest ranging from 8% to 20% by midcentury relative to the previous five decades, with individual model uncertainty regarding the degree, direction (wetter or drier), and regional spatial characteristics (KM 3.3).[10,12,15,16,17] Rapid transitions between precipitation extremes are expected to increase across all of the Midwest by late century (2071–2100) compared to historical conditions (Figure 24.1).[17,18] Amplified precipitation variability and more frequent wet–dry transitions increase the risks of transient drought and harm to crops, requiring changes in management systems to maintain food security.[19,20,21]

## Change in Frequency of Transitions Between 1-Month Precipitation Extremes




**The frequency of wet–dry and dry-wet transitions across the Midwest is projected to increase by late century (2071–2100).**

**Figure 24.1.** Transitions between wet and dry periods are expected to become more frequent across the Midwest. Observed changes in transition frequency (from wet to dry or dry to wet) are based on the Standardized Precipitation Index (SPI), represented by the difference between the periods 1951–1980 and 1981–2010 (historical change, panel **a**). SPI is a common statistical index that quantifies the relative intensity of drought or wetness, and monthly SPI values are utilized to show transitions over short periods. Projected changes in transition frequency under low (SSP1-2.6; **b**), intermediate (SSP2-4.5; **c**), and very high (SSP5-8.5; **d**) scenarios are represented by the difference between the periods 2071–2100 and 1981–2010. The black boundary outlines the Midwest region. Black dots indicate grid cells where the model-projected transition frequency is significantly different from the historical climatology. Adapted from Chen and Ford 2023[18] [CC BY 4.0].

Although average corn and soybean yields increased in recent decades in the Midwest,[22] both excessive moisture (flooding) and extreme droughts significantly decreased corn yields in some locations and years by up to 37%.[2,23] Excessive spring moisture has delayed corn planting by up to a month,[24] while episodic droughts have reduced yields[2] despite increasing annual rainfall.[25]

Future projections suggest further changes in seasonality and increases in variability. Earlier snowmelt is expected to increase daily maximum spring streamflow.[26] Intermediate (RCP4.5) to very high (RCP8.5) scenarios show both an increase in the frequency of wet springs and decreasing summer precipitation and drier soils.[15,27,28] More intense precipitation during the early spring, when soils are largely uncovered and wetter, increases soil erosion[3] and leaching of nitrogen fertilizer.[10] Additionally, water quality concerns (KM 24.5) are compounded due to more frequent spring manure storage overflow and increased pressure on farmers to spread manure early.

Temperature increases directly affect crop development and physiology[29,30,31] and lead to increases in evapotranspiration and stress during dry conditions.[32] While daily minimum temperatures have increased, daytime maximum (summer) temperatures have cooled in some areas of the Midwest (1991–2021 compared to 1901–1960; see Figure 2.4). This is an important trend for the Midwest and differs from that of other regions (Figure 3.11). Often referred to as the "warming hole,"[33] this trend may be partly explained by the expansion of croplands and increased transpiration over parts of the Midwest and Northern Great Plains (KM 25.2).[34,35,36,37,38] Increased transpiration may have also induced observed summer rainfall increases over parts of the region.[34] These changes may have contributed to improved corn yields.[39,40,41] Projections across a range of scenarios (low [SSP1-2.6] to very high [SSP5-8.5]), however, show that rising temperatures will reduce corn and soybean productivity while maintaining wheat production by the end of the century.[31,42,43] Higher temperatures also increase atmospheric vapor pressure deficit (VPD), enhancing crop water loss. Without expansion of irrigation, projected increases in VPD are expected to limit corn yields.[44,45]

Irrigation in the Midwest affects climate as well. Across the Wisconsin Central Sands region, for instance, irrigated agriculture, compared to rainfed agriculture, has contributed to decreased maximum temperatures, increased minimum temperatures, increased VPD, and decreased evaporative demand.[46] This land-use change/microclimate complexity introduces uncertainty regarding future projections of temperatures and moisture across the Midwest (KM 6.2).

Animal production in the Midwest is also vulnerable to climate change. Increases in winter and spring precipitation and temperature are expected to result in muddier paddocks and pastures, which can decrease fetal growth during late gestation.[47,48,49] Perennial forage crops are under a greater risk of winter injury with climate change because of a greater frequency of above-freezing temperatures during winter.[23] However, there are potential gains in forage productivity with a warmer and wetter climate, longer growing seasons, and higher carbon dioxide concentrations, although with potential declines in quality.[50] Other important livestock impacts include feed shortages, loss of shade structures, nutritional restrictions, disease transmission, and biosecurity concerns (e.g., feral hogs and waterfowl may contaminate existing stocks as they seek higher ground).[51] Increasing temperatures and higher dewpoints place demands on livestock management and housing needs to limit productivity losses or mortality. Heat stress limits livestock production[51,52] and dairy quality.[53] Under intermediate (RCP4.5) and very high (RCP8.5) scenarios, more intense heat abatements (e.g., fans, misting, sprinklers, ventilation) could be necessary to sustain recent production increases,[54] and environmental impacts on dairy production will increase by 2050.[55]

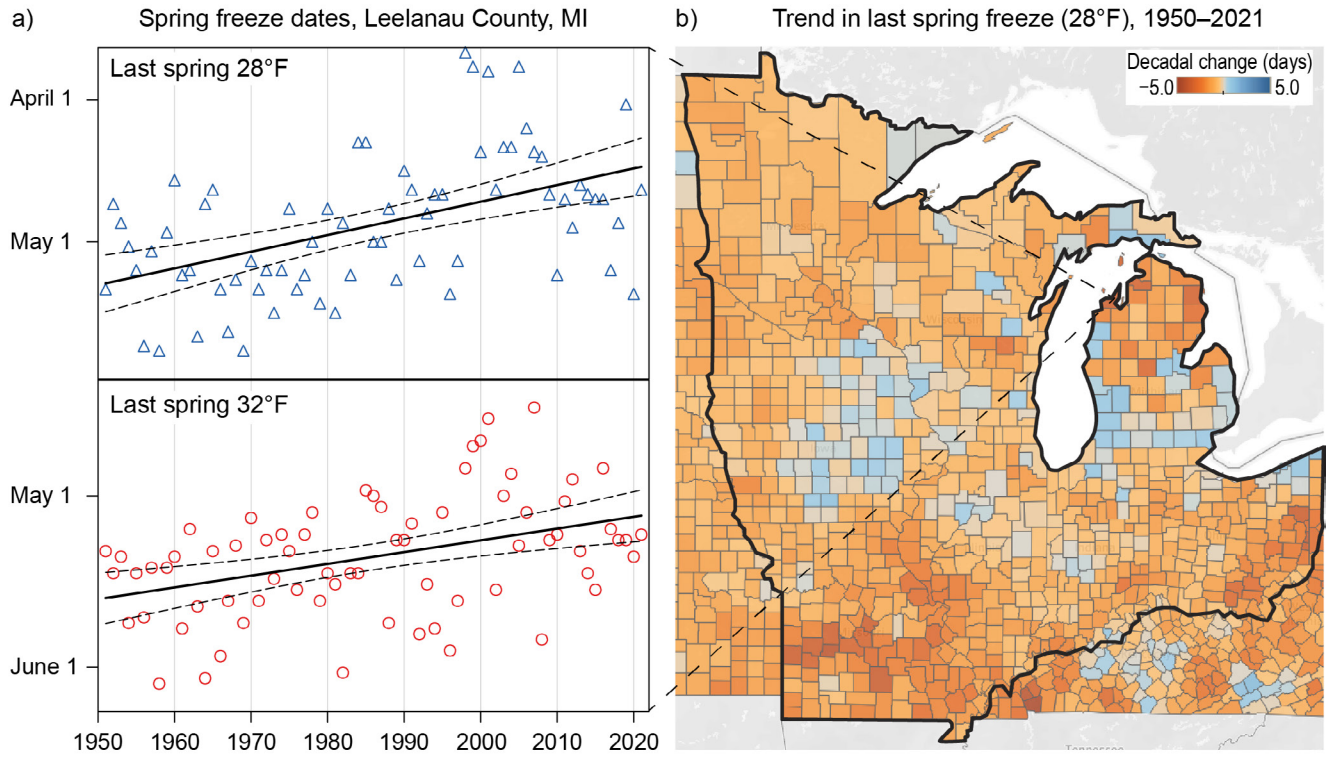
Specialty crops, such as tree fruit and vegetables (e.g., pumpkin and berries), represent a $7.1 billion industry (in 2022 dollars) and have higher potential market values and production-related risks than commodity crops due to their dependence on flavor and appearance.[56,57] Cold injury and damaging frosts during the spring are concerns for both perennial and annual crops (Figure 24.2), and excessive moisture has been associated with significant crop losses for growers throughout the year.[58] Early-season flowering followed by spring freezes (Figure 24.3) has resulted in premature phenological development of tree fruit crops, erratic flowering, and increased risk of freezing injury in April and May.[23,58] Current understanding of future impacts on specialty and horticultural crops across projected climate changes is limited. As temperatures increase, shifts in the timing and growing zones of crops have caused observed pollinator population declines that have translated directly into decreased crop production.[59,60,61] Projected temperature increases suggest continued challenges related to crop growing zones and timing.[62]

## Freeze-Damaged Apple Blossoms

**Early warmth and flowering followed by freezing temperatures in the spring poses risks to perennial and annual crops.**

**Figure 24.2.** Apple blossoms are damaged by a freeze event on May 9, 2020, in Berrien County, Michigan. Photo credit: ©Dr. Mike Reinke, Michigan State University.

## Trends in Last Freeze Dates for Spring




**Last spring freezes are occurring earlier over most of the Midwest region.**

**Figure 24.3.** (**a**) Trends (solid black lines) show that the last date in spring when minimum temperatures fall to either 28°F or 32°F in Leelanau County, Michigan, are occurring earlier in the year. For example, the last 28°F temperature commonly occurred after May 1 during the 1950s–1970s, with earlier dates noted since the 1980s. Note the large variability in dates. The statistical significance of the trends (dashed black lines; based on a 95% confidence interval) shows the range of values of the trend line based on the observed dates. In all cases, these confirm there is a trend toward earlier last freeze dates. Panel (**b**) shows change in the number of days per decade of the last spring freeze (28°F) over the period 1950–2021. The black boundary outlines the Midwest region. Orange shading indicates trends toward earlier last spring freeze dates, blue shading indicates trends towards later last spring freeze dates, and gray shading indicates no trend. Adapted with permission from the Midwestern Regional Climate Center's Freeze Date Tool (https://mrcc.purdue.edu/freeze/freezedatetool). Map base layer on right is ©Mapbox ©OpenStreetMap.

Evidence suggests that pest distributions have shifted northward since the early 20th century, and projections indicate that increasing temperatures will allow pests (e.g., brown marmorated stink bug, corn earworm, Japanese beetle, Mexican bean beetle, and potato leafhopper) to continue expanding northward across the Midwest.[63,64,65,66,67,68] Warming winters lead to insect population expansion throughout the Great Lakes (e.g., Kiefer et al. 2021[69]), while hotter, drier conditions exacerbate yield loss from weed competition.[70] Higher dew points (humidity) increase disease risk for numerous crops, including soybean and apples.[21,71,72]

Most Midwestern row crops are insured, providing growers with some economic security against weather- and climate-related risks.[73] However, US crop insurance losses continue to rise, with an estimated $31.9 billion (in 2022 dollars) attributed to climate change over the last three decades.[74] Drought payments represent the largest percentage of indemnities, although wetness losses are increasing.[75] Evidence suggests an overall decline in drought across the region since 1895;[76] however, an increased occurrence of flash drought (rapid depletion of soil moisture), along with soil degradation[77] and more productive crops,[8] has resulted in moisture stress to crops and native vegetation.[78,79] Damages from droughts and other climate-related financial losses have implications on farmers' mental health as well (KM 24.3).

## *Climate-Smart Agriculture*

According to the United Nations Food and Agriculture Organization, "climate-smart agriculture defines an agriculture that sustainably increases productivity [and] resilience (adaptation), reduces/removes GHGs (mitigation), and enhances the achievement of national food security and development goals."[80] Climate-smart strategies include, but are not limited to, the use of cover crops, reduced- or no-tillage operations, improved nutrient and manure management, wetland and grassland management, agroforestry, bioenergy crops, on-site carbon sequestration, and agrivoltaics (the integration of agricultural production activities and solar energy generation; Figure 24.4). However, there are uncertainties about the climate benefits and detriments of these techniques, particularly in field settings.[81] Cover crops can improve soil health, reduce erosion, and increase soil organic carbon. Five percent of agricultural fields in the Midwest were cover-cropped in 2017, up from 2.6% in 2012.[82] A reduction in yields for cash crops may deter further adoption of cover crops, and recent analyses suggest that non-legume cover crop adoption reduced maize yields by 3.9% to 5.5% in the Midwest.[82,83] Billions of dollars of investment to encourage producers to test various climate-smart practices have come from federal programs and legislation. Precision agriculture, which maximizes the efficiency of input application (e.g., fertilizers, herbicides) allows for homogeneously managed zones within the same field.[84,85] Such approaches have the potential to increase production efficiency; increase resilience to climate-related risks, particularly the loss of nitrogen fertilizer;[86,87] and yield co-benefits for Midwestern ecosystems (KM 24.2). Corn remains the major bioenergy crop in the US, providing ethanol as a biofuel.[88] Whether corn ethanol is a climate-smart practice is heavily debated.[88] Second-generation biofuels from cellulosic biomass feedstocks, including dedicated energy crops (grown specifically for energy and not food production); agricultural crop residues (materials left on land after crop harvest); and wood residues have greater potential to reduce greenhouse gas emissions, with limited adverse impacts on food crop prices and indirect land-use changes compared to corn ethanol.[89,90,91] Additional techniques concerning animal agriculture and greenhouse gas emissions are explored in KM 11.1.

## Environmental Impacts from Conventional Versus Climate-Smart Practices

**Climate-smart agricultural strategies may have adaptation and mitigation advantages that balance agricultural needs and environmental impacts.**

**Figure 24.4.** The figure shows examples of conventional and climate-smart production methods: (**clockwise from top center**) wheat field in Brownsburg, Indiana; spring corn under fair skies in southwest Ohio with infield soil sampling probe; outlet from water control structure to agricultural drainage ditch; inter-seeded annual ryegrass, clovers, and radishes growing in young corn in Carroll County, Iowa; macrotopograhic feature (ridge and swale) on a wetland restoration easement in Starke County, Indiana; planting green: no-till drilling soybeans into standing cereal rye in Washington County, Iowa; Forage Systems Research Center in Missouri works to improve the quality of forage grass, promotes management-intensive grazing, rotational grazing, cattle management, and the economics of beef and forage; an example of agrivoltaics—combining solar energy production on agricultural production lands; farmer tilling fields: traditional practice to break up soil in preparation for planting; farmer harvesting soybean with combine. The center diagrams compare the agricultural needs (blue ovals and text) with environmental impacts (green ovals and text) for both conventional and climate-smart agriculture. As shown, there is an imbalance between the agricultural needs and environmental impacts of conventional agriculture (represented by the blue and green ovals); whereas climate-smart agriculture may provide more balance between the two. Adapted with permission from Foley et al. 2011.[92] Photo credits: (top left; left, second from top) United Soybean Board [CC BY 2.0]; (top center) Carly Whitmore, NRCS; (top right) ©Elizabeth Hawkins; (right, second and third from top; bottom left) NRCS/SWCS photo by Lynn Betts [CC BY 2.0]; (bottom right) Carly Whitmore, NRCS; (bottom center) Kyle Spradley [CC BY 2.0]; (left, third from top) ©Tony Mancuso.

## Key Message 24.2

## Adaptation May Ease Disruptions to Ecosystems and Their Services

Ecosystems are already being affected by changes in extreme weather and other climate-related changes, with negative impacts on a wide range of species (*likely*, *high confidence*). Increasing incidence of flooding and drought is expected to further alter aquatic ecosystems (*likely*, *medium confidence*), while terrestrial ecosystems are being reshaped by rising temperatures and decreasing snow and ice cover (*very likely*, *high confidence*). Loss of ecosystem services is undermining human well-being, causing the loss of economic, cultural, and health benefits (*medium confidence*). In response, communities are adapting their cultural practices and the ways they manage the landscape, preserving and protecting ecosystems and the services they provide (*low confidence*).

### *Risk*

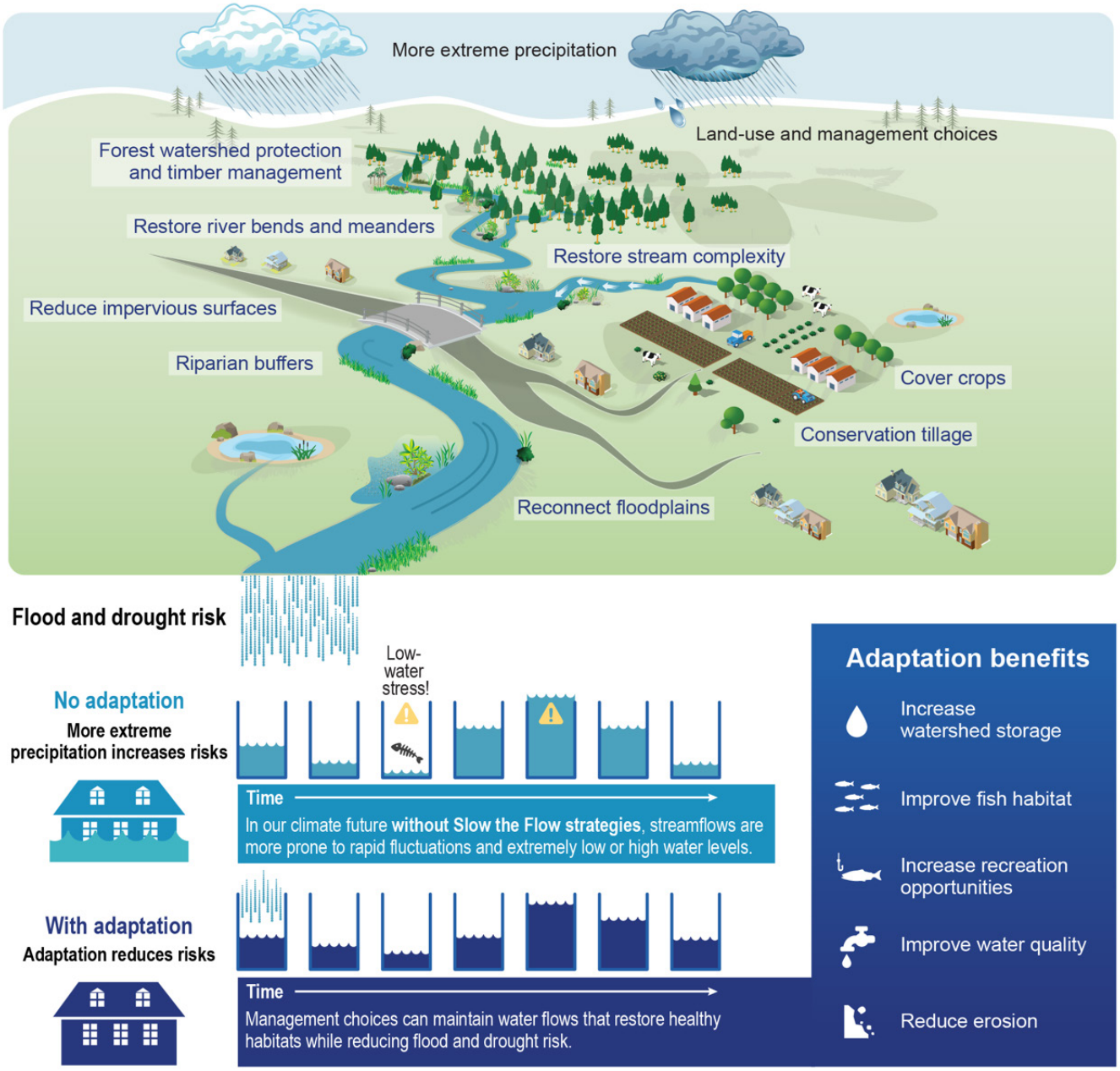
The Midwest is home to many communities and cultures that appreciate and rely on fish, wildlife, waters, and lands. Indigenous communities throughout the Midwest recognize natural resources as persons and extended family (a kin-centric viewpoint) and at times may use terminology such as relatives or beings to refer to them.[93] These relatives support intergenerational continuity, heritage, and spiritual practice. Fishing, hunting, and wildlife viewing are common recreational activities and contribute billions of dollars to the regional economy.[94] Exposure to natural environments enhances human well-being and health,[95] while limited access to natural resources contributes to health inequality.[96]

### *Impacts*

Midwestern aquatic ecosystems are being harmed by rising temperatures and increased precipitation.[97] Climate change intersects with invasive species, land-use change, and human consumption to affect nutrient pollution, water quality, and water levels.[98,99,100,101] For example, invasive species and habitat degradation are negatively affecting walleye growth, survival, and abundance.[98,102,103,104] Mass fish die-offs due to extreme summer heat are projected to double by midcentury (under a very high scenario [RCP8.5]) in northern temperate lakes.[105] Indeed, the Fond du Lac Band of Lake Superior Chippewa has documented an increase in lethal stream temperatures and a decline in brook trout harvest.[5]

Extreme precipitation events degrade riparian ecosystems, erode river and stream banks, disperse contaminants, disrupt plant and animal cycles, and spread invasive species; however, there may be benefits to flooding, including increases in connectivity for aquatic organisms, habitat complexity, and size of the floodplain.[106] Reduced snowmelt is projected to shift spring peak flow earlier in the year.[107,108] Rapid transitions in hydrology (Figure 24.5) and increasing temperatures are projected to cause widespread changes in stream conditions, shifting habitats for invertebrates and fishes.[109] While broad declines in brook and brown trout populations are projected, streams with enhanced groundwater sources have demonstrated resilience to warming and the ability to maintain a viable fishery.[110] Climate-driven changes in heavy rainfall are magnified by land use, with pronounced negative effects in urban[111] and agricultural watersheds.[26]

## Extreme Precipitation Impacts




**Extreme precipitation events have adverse impacts on aquatic and terrestrial ecosystems, human health, infrastructure, and economies. Conservation and management strategies can help moderate these impacts.**

**Figure 24.5.** Extreme precipitation events can degrade aquatic ecosystems, threaten human health and safety, damage infrastructure and communities, and yield billions of dollars in economic damage. The conservation and management of natural lands can reduce these negative effects—reducing erosion and flood risk, improving water quality, increasing carbon sequestration, and reducing the economic cost of flooding. This conceptual drawing, showing a Midwestern landscape with an extreme storm on the horizon and water flowing into streams and rivers, illustrates how land management choices affect downstream flooding, infrastructure, and ecosystem services. Landscape features and land management practices that slow the flow of water across the surface can improve habitat and water quality, reduce flood and drought risks, and have a variety of other benefits. Adapted with permission from Palmer et al. 2020.[112]

As in the Northern Great Plains (KM 25.4), agricultural expansion threatens Midwestern grasslands[113] via habitat loss and land fragmentation, which exacerbates the vulnerability of grassland wildlife.[114,115] In Indiana, high temperatures and drought contributed to the local extirpation of the endangered Karner blue butterfly,[116] and portions of the Midwest may become inhospitable for the monarch butterfly due to climate change.[117] While the composition of grassland communities is changing in response to climate change, land use, and management,[118] the adoption of mowing and prescribed burning may offset global and regional drivers to retain biodiversity in these threatened ecosystems.[119,120]

Increasing temperatures are projected to increase wildfire risks to Midwestern forests.[121,122,123] Flash droughts, characterized by sudden onset and rapid intensification,[124,125] have increased in frequency since 1980—although it is unclear whether current frequencies reflect a departure from the past (i.e., before the instrumental record began[126]). Flash droughts not only impact crops (KM 24.1) but also induce significant water stress in thin-soiled forests, inciting pathogen infection that increases tree mortality.[127] Additionally, climate change combined with river management for navigation strains the health of floodplain forests that are important hotspots of ecological activity.[128,129]

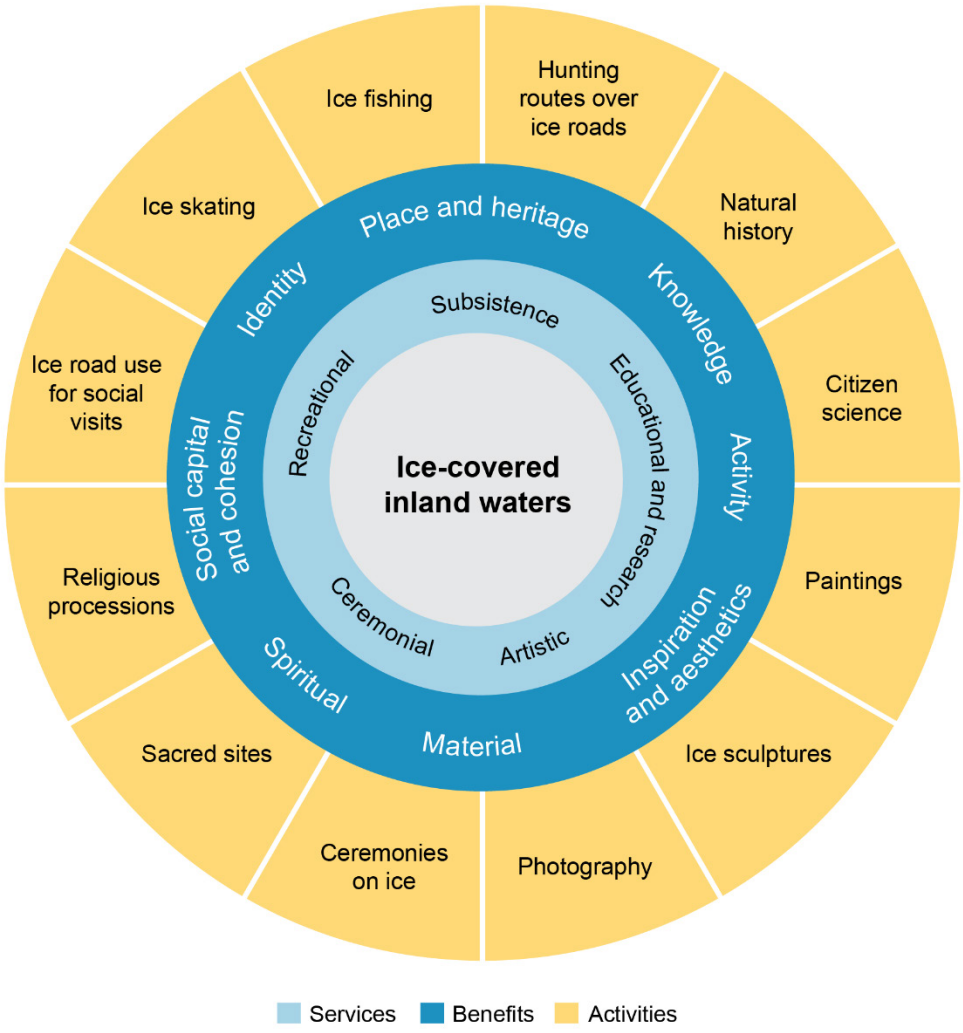
The threat of invasive species is amplified by climate change.[130,131] However, invasive species can be perceived in different ways: many Indigenous communities have holistic views of invasives, or non-local beings, who encompass both positive and negative attributes. For example, dandelions and common plantain are used medicinally in Anishinaabe communities. Understanding the gifts and teachings that beings have can change our interactions and resource management.[93,132]

Warming has shortened the length of persistent cold conditions and decreased snow cover in the Upper Midwest.[133,134] Snow supports the survival of boreal wildlife, providing insulation from cold conditions.[135] Some types of wildlife, such as moose, are threatened by warming winter conditions;[133] declining moose populations have been recorded in the 1854 Ceded Territory over the last three decades.[136,137] This loss, in turn, has cascading impacts on cultural practices, human well-being, subsistence harvesting, and tourism.[133,138,139]

Climate change accelerates the loss of beings, access, and connection to the land for Indigenous Peoples (Ch. 16).[133,140,141,142,143] Wild rice is one of the most vulnerable culturally significant species to Midwest Tribes,[5,144] and harvest rates have decreased due to warming and altered hydrology,[136,145] potentially leading to a loss of cultural identity.[5,146] Sugar maple is also culturally and economically important to Indigenous communities.[133,145,147] Warming winters have altered the timing and length of maple sugaring.[136,145] Seasonal changes and shifting habitats can impact Traditional Knowledge, language, physical health, and mental well-being by altering the timing of cultural ceremonies, availability of beings needed for the ceremonies, and potential loss of culturally significant relatives (KMs 8.2, 16.1).[145,148]

Nature-based recreation is transitioning, affecting opportunity, economy, and safety (KM 8.3). For example, climate change limits the availability of fish such as walleye and trout, sometimes leading to reduced catch limits[104] and food insecurity.[149] Ice cover, an important feature of northern lake systems, is declining in response to rising winter air temperatures,[150] with the most abrupt changes beginning in the 1990s.[4] Loss of ice cover is projected to continue through the end of the century, with greater losses under high scenarios,[150] threatening some cultural activities and services (Figure 24.6).[151] Winter drownings have also increased along with temperatures, which have decreased ice cover.[152]

### Ecological Services of Ice-Covered Inland Waters




**Rising winter temperatures are decreasing inland lake ice cover and the associated ecosystem services, benefits, and activities it provides.**

**Figure 24.6.** Ice-covered inland waters provide humans with important cultural ecosystem services (light blue ring), benefits (dark blue ring), and activities (yellow ring) that are central to people's well-being, culture, and identity across the Midwest. Adapted from Knoll et al. 2019[151] [CC BY 4.0].

## *Nature-Based Solutions for Adaptation and Mitigation*

Land managers are actively managing Midwestern forests to adapt to climate change[153] by reducing stressors, restoring native species diversity, increasing structural diversity (e.g., variation in age structure), and shifting forest composition to species better adapted to future climate conditions.[153,154] Additional studies can inform the introduction of species adapted to future climate to achieve desired forest management outcomes.[155]

Fish managers have ways to reduce the effects of increased water temperatures, novel invasive species, and other climate-driven changes.[97] They have combined socioeconomic and ecological data to prioritize lakes and identify suitable management techniques.[156] Current management interventions include acquisitions and easements, reducing runoff, protecting in-lake habitats, managing invasive species, changing harvest regulations, and adjusting stocking priorities.[156] Improvements in lake modeling and forecasting of harmful

algal blooms, as well as better information about invasive species and resilient fisheries, have the potential to improve adaptation efforts.[157]

Climate adaptation and mitigation can be achieved in part through nature-based solutions, including the protection and management of natural lands. These approaches have the additional advantage of providing social, ecosystem, and economic benefits.[158,159] Since 1980, the Midwest has incurred $49–$109 billion (CPI-adjusted to 2022 dollars) in economic damages due to flooding,[160] with losses projected to increase with further climate change.[161] Natural floodplains can reduce flood damages and yield benefit-to-cost ratios of up to 5 to 1.[162] Moreover, a targeted 10% increase of wetland area within the Mississippi River basin could decrease nitrogen loading to the Gulf of Mexico by more than 40%.[163] Additionally, climate-smart strategies on agricultural lands (Figure 24.4)[164] can yield co-benefits for Midwestern ecosystems.

There is also growing enthusiasm for natural climate solutions, which are specifically designed to increase carbon storage or decrease greenhouse gas emissions through conservation, restoration, and improved land management.[165,166,167,168] Some Midwestern forests are already being managed to bolster carbon storage,[169] and there is much room for expansion of these practices in the region (KMs 7.2, 8.3). Ongoing changes in the climate and atmosphere are expected to accelerate growth of the region's grasslands, which, depending on how they are managed, could increase their carbon storage.[170] Extensive peatlands in the region historically sequestered carbon, but much of this carbon has already been released by draining wetland areas.[171,172]

The long-term mitigation potential of Midwestern ecosystems has large sources of uncertainty related to climate-driven risk factors such as fire, drought, and pests;[165] offsets from increased soil microbial respiration;[173] and warming-induced losses of carbon stored in peatlands.[174]

Tribal Nations have made considerable progress in adaptation, including collaboration on guidance, vulnerability assessments, and implementation (KM 21.4; Ch. 16).[132,144,175] Adaptation strategies vary among Tribal Nations and their values. For example, one being might be a suitable substitute for another, such as birch trees instead of sugar maples for syrup tapping; however, beings that are tied tightly to a Tribal Nation's cultural identity (e.g., wild rice) cannot be substituted.[145] Therefore, adaptation strategies for those beings could mean collaborating and building relationships with Tribes and agencies outside of traditional harvesting lands and jurisdictional boundaries.[132,145] Inclusion of cultural knowledge and language can strengthen adaptation planning and implementation.[132,141,143,144] Guidance for incorporating this information and Tribal input by non-Tribal entities can inform respectful and reciprocal collaboration.[132,176,177]

## Key Message 24.3

## Climate Adaptation and Mitigation Strategies Improve Individual and Community Health

Climate change has wide-ranging effects on lives and livelihoods (*very likely*, *very high confidence*), healthcare systems (*high confidence*), and community cohesion (*high confidence*). These diverse impacts will require integrated, innovative response from collaborations between public health and other sectors, such as emergency management, agriculture, and urban planning. Because of historical and systemic biases, communities of color are especially vulnerable to these negative impacts (*very likely*, *very high confidence*). Mitigation and adaptation strategies, such as expanded use of green infrastructure, heat-health early warning systems, and improved stormwater management systems, when developed in collaboration with affected communities, have the potential to improve individual and community health (*high confidence*).

### Risk

The health of Midwestern populations is at risk from increased extreme heat, precipitation, drought, and flooding, along with reductions in air quality and increased incidence of vector- and waterborne illnesses (Ch. 15). Physical injury and illness resulting from climate-related hazards may also influence mental health and can reduce quality of life and community function as traditional forms of connection and culture are lost or diminished.[178,179]

An individual's exposure and sensitivity to climate change are influenced by preexisting health conditions, age and gender, race and ethnicity, access to resources, and the level of local adaptive capacity.[179,180,181,182] Therefore, climate change impacts on health are not distributed equally across populations. Historical policies and systemic racism have created conditions that leave lower-income individuals and people of color more vulnerable to climate-related hazards (KMs 15.2, 16.1).[179,182,183,184] Environmental and social conditions such as old or deteriorating housing stock, inadequate tree cover, poor or degraded stormwater infrastructure, increased exposure to air pollution, limited transportation access, and lack of preventive healthcare services amplify climate-related hazards in the Midwest.[181,183,185]

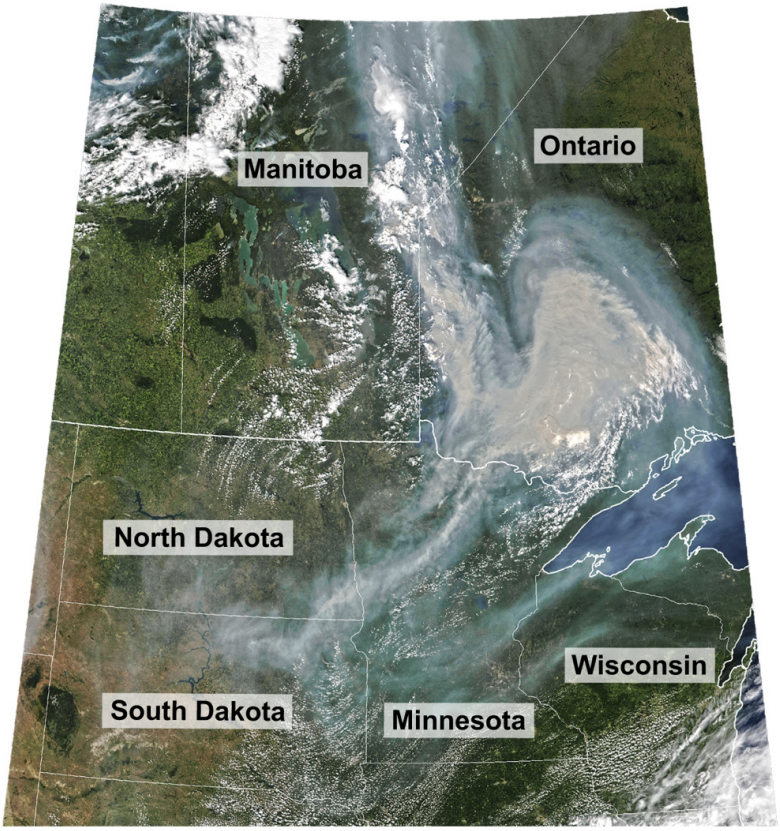
### Impacts

Rising temperatures can increase the production of ground-level ozone and particulate matter (KM 14.1). Exposure to these air pollutants can cause or worsen cardiovascular and respiratory illnesses and lead to premature death.[186,187] Future warming under a very high scenario (RCP8.5) is projected to increase exposure to ground-level ozone by midcentury, with higher ozone-attributable death rates in counties in the Midwest and Great Plains than in the rest of the United States.[188] This association may be impacted by population factors, such as density and baseline death rates.[188] Mitigation efforts that reduce ozone can yield large reductions in associated healthcare costs.[189]

Projected increases in extreme heat events across the Midwest amplify the risk of heat-related and respiratory illnesses. A July 2012 extreme heat event in Wisconsin was associated with approximately $290.3 million (in 2022 dollars) in damages due to loss of life, hospitalizations, lost wages, and other health-related costs.[190] By the end of the century, approximately 1,200 deaths related to extreme heat would be avoided under an intermediate scenario (RCP4.5) compared to a very high scenario (RCP8.5).[191]

While many of the worst wildfires occur in the western US, there are scattered areas of high wildfire risk throughout the Upper Midwest (Focus on Western Wildfires).[192] Wildfire smoke from both local and distant sources (Figure 24.7) poses a threat to human health by aggravating cardiovascular and respiratory conditions such as heart arrhythmias and asthma.[89,193] A study of hospital admissions across the US between 2006 and 2015 found that an increase of 10 micrograms per cubic meter in wildfire-related particulate matter in a hospital's zip code was associated with a nearly 3% increase in probability of an intensive-care-unit admission.[194] Compared to other US census areas, this association was most consistent across Midwestern zip codes. This may be due to the larger population in this region compared to other study regions or the lack of personal protective behaviors.[194] Based on very high (RCP8.5) and intermediate (RCP4.5) future climate projections, many Midwest counties will experience increased exposure to wildfire smoke.[195]

## Impacts from Wildfire Smoke in the Midwest




**Wildfire smoke from both local and distant sources threatens human health.**

**Figure 24.7.** This satellite image shows wildfire smoke from Canada moving down over the northern Midwest on July 11, 2021. Satellite image credit: Joshua Stevens, NASA Earth Observatory, using VIIRS data from NASA EOSDIS LANCE, GIBS/Worldview, and the Joint Polar Satellite System (JPSS).

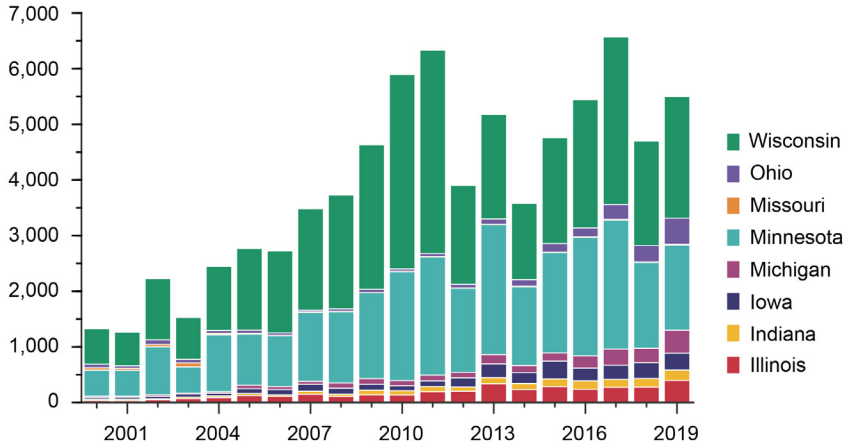
Increasing spring and fall temperatures are leading to rising pollen counts, which can worsen allergies, asthma, and other respiratory conditions (KM 14.4).[196,197] By 2050, increased oak pollen is projected to lead to a 7% annual increase in asthma-related emergency room visits for the Midwest under a very high scenario (RCP8.5) compared to 2% under an intermediate scenario (RCP4.5).[198] Notably, when sensitive individuals are simultaneously exposed to allergens and air pollutants, respiratory reactions can become more severe.[199] Black, Hispanic, and Indigenous populations tend to be disproportionately exposed to air pollution[181] and have the highest rates of asthma and asthma-related deaths and hospitalizations in the United States.[200]

The amount of precipitation falling in the most intense 1% of events increased significantly (45%) in the Midwest between 1958 and 2021 (Figure 2.8a). Under a global warming level of 3.6°F (2°C), extreme precipitation intensity is projected to increase 10%–15%, and perhaps more than 20% in some areas (Figure 2.12). Public health concerns related to flooding in the Midwest include drowning and injury, exposure to mold or waterborne pathogens, economic losses and fiscal strain, employment loss, mental stress, disruption of essential health services, and displacement from the community.[179,184,201,202]

Increases in extreme rainfall are stressing stormwater systems across urban and rural landscapes in the Midwest (KM 24.5).[164,201] Resulting sewage overflow threatens surface water and water distribution networks and increases exposure to waterborne pathogens.[201] By midcentury, precipitation changes are projected to increase the rate of gastrointestinal illness among children due to contaminated drinking water.[203] Under a very high scenario (RCP8.5), some Midwest households that rely on private wells for drinking water, most of which are outside of urban areas, are projected to be at higher risk for nitrate contamination from heavy rainfall and flooding.[204]

Rising temperatures, particularly in winter, and increasing precipitation contribute to the geographic spread of disease-carrying vectors (e.g., ticks and mosquitoes) into and across the Midwest.[205,206] Lyme disease, caused by the bacterium *Borrelia burgdorferi*, is the most prevalent vector-borne disease in the United States and is now endemic to the Midwest (Figure 24.8).[207] Health costs related to Lyme disease are substantial. One study estimated that in 2012, the health-related costs of treating Lyme disease in Michigan, which at the time was not a high-incidence state, was approximately $9 million (in 2022 dollars).[190] The tick species *Amblyomma americanum*, linked to ehrlichiosis and other serious diseases, has already been reported in the Upper Midwest, and projections indicate considerable potential expansion throughout this century.[208]

### Midwest Region Lyme Disease Case Counts by State (2000–2019)




**Lyme disease incidence has increased across the Midwest.**

**Figure 24.8.** The graph shows annual reports of Lyme disease incidence across the Midwest between 2000 and 2019. Factors such as rising temperatures, increased precipitation, warmer winters and land-use change have contributed to an increase in the incidence of Lyme disease across the region. Figure credit: University of Minnesota Climate Adaptation Partnership, NOAA NCEI, and CISESS NC.

Milder winter temperatures and changes in precipitation patterns are also increasing the risk of mosquito-borne arboviruses such as dengue, chikungunya, Zika, yellow fever, and West Nile virus.[209] By 2050, areas like the Ohio Valley are projected to have approximately 99–201 annual cases of West Nile virus under an intermediate scenario (RCP4.5) or 112–231 annual cases under a very high scenario (RCP8.5).[210]

Stress associated with experiencing climate-related disasters is impacting the mental health of people living in the Midwest[179,211] and is expected to increase as the frequency of extreme events rises. The trauma caused by a disaster, such as losing one's home, job, or livelihood or being displaced from one's community, can contribute to chronic depression, anxiety, and post-traumatic stress disorder.[212,213] In addition, people can suffer a loss of social connections, bear witness to people being harmed and landscapes destroyed, and confront an uncertain future, any of which can trigger or intensify adverse mental health conditions.[178,214] Farmers and others dependent on agriculture for their livelihood are particularly at risk.[212,215,216] Many rural Midwesterners already experience obstacles to utilizing healthcare services,[217] including mental health services.[218,219]

## *Climate Resilience for Healthier Outcomes*

Without efforts to reduce emissions and promote climate resilience, the Midwest will experience an increase in climate-related deaths, injury, and disease and a decrease in mental wellness.[220,221] Furthermore, because these health outcomes are linked to key social and environmental determinants of health, they are expected to disrupt community well-being, with costs and consequences for livelihood, social and cultural connections, education, transportation, and access to essential services.[178,182,221,222] Health disparities tied to race, ethnicity, age, and income are linked to an inequitable distribution of these climate-related health outcomes at individual and population levels.[179,184]

Actions and investments to reduce climate-related health and community impacts such as increased tree cover, weatherization programs, improved stormwater management, heat-health early warning systems, and culturally relevant climate education and climate services (Box 24.1) can yield multiple benefits for individual and community health while helping to advance more equitable climate adaptation.[182,223,224,225,226,227] Sufficient data, technical services, and tools on climate-related health risks, racial and socioeconomic disparities, and socioenvironmental determinants of health would help increase the effective management of emerging and anticipated climate and health-related risks.[182,204,227] For example, the CDC has advanced a framework for cross-sector collaboration that identifies a broad range of resources to reduce climate-related health risks.

Leadership efforts by the emergency management sector in the Midwest to address climate threats to individual and community health highlight the important role for this sector in adaptation planning.[220,228,229] The increased frequency of extreme events is expanding the need for more resources to support disaster preparedness and response, especially for vulnerable communities.[182,228,230]

## Box 24.1. Midwest Educational Resources

The Midwest has a rich and expanding body of formal and informal climate education and services available to educators and resource managers of all ages and backgrounds. These efforts help build a climate-informed and responsive society and connect to impacts as well as adaptation and mitigation activities discussed throughout this chapter. Built on the National Research Council (NRC) Framework for K–12 Science Education,[231] educators from across the country created the Next Generation of Science Standards (NGSS), which includes contemporary climate science.[232] Incorporation of these standards varies across the Midwest. Illinois, Iowa, and Michigan have adopted the NGSS, while others have developed their own standards based on the NRC framework.[233] In response, educators have created new climate curriculums and activities for students across K–12 (e.g., Muhich and Rood 2022[234]). Recent federal investments, such as one establishing the Midwest Climate Adaptation Science Center,[235] augment climate research and outreach across the region, connecting with more communities and developing a stronger climate adaptation and community of practice. Since the publication of the Fourth National Climate Assessment in 2018, coordinated efforts have increased among extension professionals, who help translate climate research into practice to help rural and urban communities prepare for and respond to climate change. These and many other university, Tribal, and private entities are collaborating to expand the breadth and reach of climate education and services across the Midwest.

## Key Message 24.4

## Green Infrastructure and Investment Solutions Can Address Costly Climate Change Impacts

Increases in temperatures and extreme precipitation events are already challenging aging infrastructure and are expected to impair surface transportation, water navigation, and the electrical grid (*likely*, *medium confidence*). Shifts in the timing and intensity of rainfall are expected to disrupt transportation along major rivers and increase chronic flooding (*likely*, *high confidence*). Green infrastructure and public and private investments may mitigate losses, provide relief from heat, and offer other ways to adapt the built environment to a changing climate (*medium confidence*).

### *Risk*

Midwest infrastructure, including dams, bridges, roads, wastewater facilities, and energy generation and distribution systems, need repair,[236] with estimated costs for upgrading these systems totaling $7,547 (in 2022 dollars) on average per capita across the Midwest. Projected changes in precipitation and temperatures increase the risk of failure and cost. Although the Midwest has had numerous state-level and federally declared flood disasters, the risk of loss due to recurrent, underreported inland and urban flooding events increases as the frequency of intense precipitation events rises. Fluctuating water levels make efficient navigation of goods and services through the region's rivers and the Great Lakes more challenging.

### *Impacts*

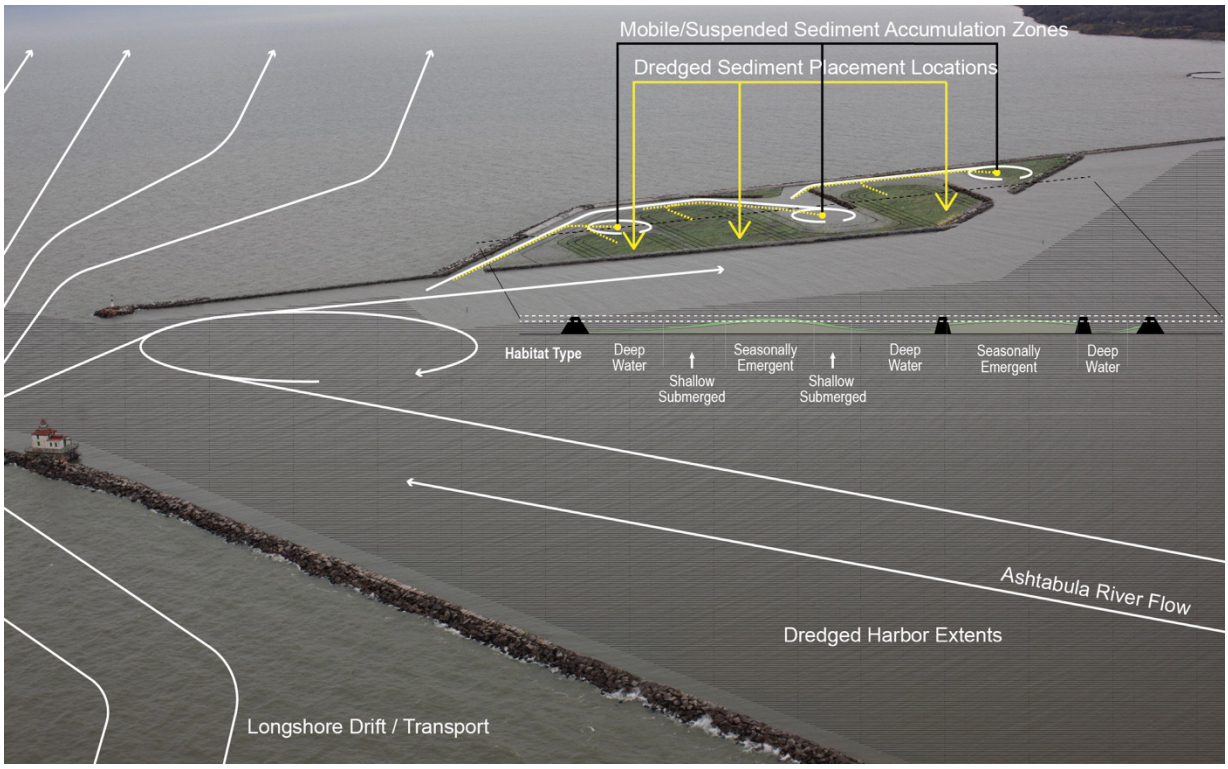
Interest in the impacts of climate change on infrastructure has grown significantly over the last decade.[237] Although improvements have been made, recent grades based on capacity, condition, funding, future need, operations and maintenance, public safety, resilience, and innovation across Midwestern states vary from a C to a D+.[236] Significant repairs are needed in surface transportation, wastewater and stormwater, dams, ports, and the energy grid. Projected increases in temperature and more intense precipitation under a very high scenario (RCP8.5) are expected to increase costs associated with rail and roads (amounting to hundreds of billions of dollars annually by 2090), with significant reductions to these estimates under an intermediate scenario (RCP4.5).[238] For instance, projected rises in temperature are expected to increase the width of cracks caused by deicing salts in reinforced-concrete bridges.[239]

The commercial transport of goods and services along the major rivers (Mississippi, Missouri, and Ohio Rivers; KM 24.5), largely controlled by a system of locks and dams, is at risk from increased precipitation extremes. High-flow events reduce traffic on the river systems, which may be limited to daytime operation only or cease altogether. During low-flow events, channels are reduced and potentially need dredging. These hydrologic extremes increase costs and lead to delays in the delivery of commodities like food and fertilizer. Along the main stem of the Ohio River, increases in the spring (March) maximum and decreases in the fall (October) minimum flow discharge are projected for 2070–2099 under high (SRES [Special Report on Emissions Scenarios] A1B) and very high (SRES A2) scenarios, with up to a 35% change expected relative to 1952–2011.[240] Without coordinated adjustments to monitoring, water releases, and communications along the river, significant disruptions to traffic flow and volume of goods transported are expected.

Water transport is the most carbon- and fuel-efficient means of transport, especially compared to rail and truck.[241] Fluctuating Great Lakes water levels, coupled with diverse ecological and geophysical conditions, create unique coastal environments that necessitate funding and construction strategies that are closely

tied to local ecological, economic, and social conditions. The period 1998–2013 saw some of the lowest water levels on the Great Lakes in recorded history, whereas the 2020s have seen some of the highest on record.[242] Great Lakes ports (Figure 24.9) are located at the vital intersections of ecological, cultural, and infrastructural systems, and port operations attempt to serve these overlapping, and at times conflicting, value systems.[243,244,245] In some cases, ports are taking on the work of ecological restoration as well as protection, property management, and urban industrial remediation—the types of efforts that can promote industrial opportunities, urban well-being, and ecological health. A good example of this is Toledo's More Than a Port initiative.[246] Another example is the multiyear Healthy Port Futures initiative, supported by the Great Lakes Protection Fund. This project reimagines how ports can function to enhance the ecological and social health of the surrounding community and ecosystem through sediment management, as well as through the ways it informs the design and restoration of public landscapes in critical nearshore habitats across the region.

## Beneficial Use Wetland Creation for Healthy Ports




**Innovative design of coastal infrastructure, such as the Ashtabula Port, allows the built environment to deliver social and environmental services.**

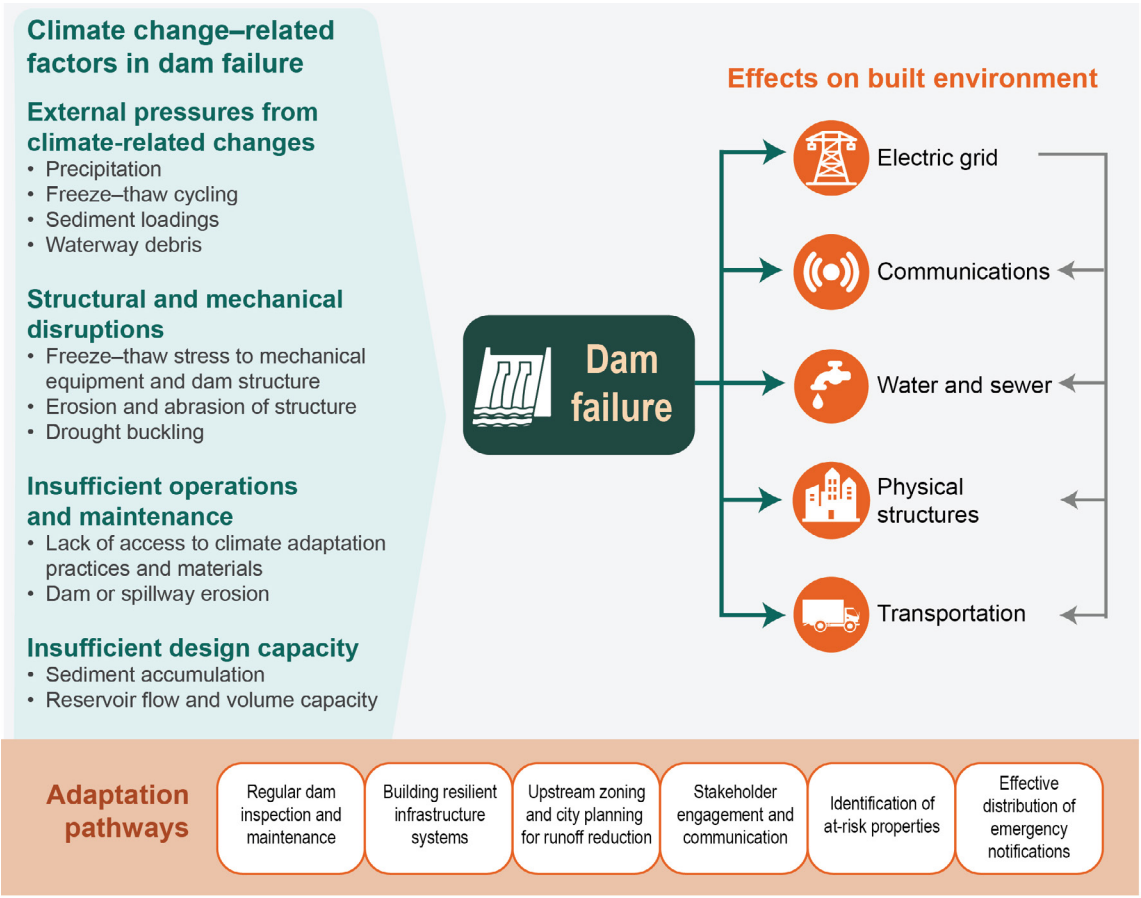
**Figure 24.9.** The image shows an overview of the harbor in Ashtabula, Ohio, the site of a wetland creation project by the US Army Corps of Engineers with support from Healthy Port Futures. This project, which works with the flow on the Ashtabula River into Lake Erie, was one of the first attempts in the Great Lakes to establish a partially open wetland system with reused dredge material. This design permits an occasional, ecologically necessary disturbance that will promote wetland complexity while also allowing for an important hydrological connection to the nearshore. The figure highlights areas of material placement (solid yellow lines) and sediment movement and accumulation (solid white lines, including sediment transported naturally along the shore). Sediment that accumulates in the wetland channels is placed in the dredged sediment placement locations (dashed yellow lines) every two to three years. This way, the project can employ an adaptive management approach and respond to successes and challenges that may arise. The project will create diverse habitat types including deep water, shallow submerged areas, seasonally emergent areas, and the adjacent open water areas (habits indicated by the light beige and green shading). The built project differs slightly from what is shown here. Adapted from Burkholder et al. 2022.[247]

An aging energy grid, combined with the extent and timing of a transition to different sources of energy generation, creates uncertainty about the impact of climate change on the grid itself. Increases in air temperature, rainfall, and the intensity and frequency of wildfires and storms are expected to disrupt grid efficiency and function, including maximum capacities and outage rates of transmission lines, transformers, and substations.[248] Climate change will reduce US transmission capacity by roughly 2%–8% during peak demand periods by 2100 across a range of scenarios (low [RCP2.6] to very high [RCP8.5]). Average summertime transmission line capacity reductions could range from 2%–6% under the same scenarios by the midcentury, with the Midwest seeing the largest reductions.[249] Transmission infrastructure failures, including those caused by mechanical failures and unplanned surges in electrical current, are projected to occur more frequently.[248] Given the strong push toward renewable energy and electrification of all systems, including transportation, it is uncertain whether the current grid will be able to handle the ongoing and anticipated changes in energy generation and distribution.

Renewable energy production in the Midwest has grown by more than 275% over the last decade,[250] reducing carbon emissions from the energy sector, although less so than in other regions. The growth of investment in renewable energy is contributing to the Midwest's economy. In Iowa, public interest coupled with public and private investment has advanced the state to the second-highest wind energy–producing state in the country and leading the Nation in megawatt capacity per capita. In Adair County, Iowa, investments by MidAmerican Energy Company have led to the installation of two large wind farms that are cumulatively expected to produce 550 megawatts of capacity to the grid and provide well-paying jobs.[251] However, the extent of growth in solar and wind power across the Midwest is constricted by a patchwork of state and local land-use laws and ordinances banning or regulating the siting of solar and wind power generation projects.[252]

Illinois, Iowa, Missouri, Wisconsin, and Minnesota are at high risk for increased riverine flood damage.[253] Of nearly 92,000 dams inventoried by the US Army Corps of Engineers, the average dam age is 61 years, an age when many dams require expensive repairs, and 75% are classified as high hazard potential. Climate-forced external pressures interact in complex ways, leading to effects on the built environment (Figure 24.10). Increased occurrence of extreme precipitation events stresses aging infrastructure and exacerbates the risk dams pose;[254] since 2018, 30 dam failures or near failures have occurred across the Midwest.

## Climate Change–Related Factors in Dam Failure




**Climate change–related factors contribute to dam failure, with cascading impacts on the built environment.**

**Figure 24.10.** The graphic shows contributing causes for dam failure related to climate change, first-order effects of dam failure on the built environment, and adaptation pathways. Dam systems may experience climate change–related impacts independently or in parallel, and these impacts can have cascading effects. Damage to transportation, power, water, and communication infrastructure can limit a community's ability to access health services. Damage to infrastructure, land, and the built environment can negatively impact local businesses and the economy. Adaptation pathways provide a basis for communities to address dam risk from a variety of system viewpoints. Figure credit: MITRE, University of Pennsylvania, American Society of Adaptation Professionals, and The Ohio State University.

Increases in extreme rainfall events (Figure 2.8) negatively impact property, public health and safety, and transportation systems. Urban and rural communities are at risk from projected increases in frequency and intensity of extreme rainfall events. Even when events are not categorized as state or federal disasters, communities and households experience property damage from basement flooding, health impacts from sewer overflows, and traffic disruptions from storm damage.[179,255] Increases in state and federally declared disasters are expected to become more frequent. NOAA's Billion-Dollar Weather and Climate Disasters tracking data now offer a detailed analysis of disasters reaching this cost impact, but smaller events are difficult to assess.[160]

Moving away from disaster-struck areas is more difficult for people with low income than it is for wealthier populations.[256,257,258] Billion-dollar disasters and smaller-scale disasters alike have led to individual property damage and, in some cases, complete loss. A history of repairing buildings after repeated disasters has led to cases where structures have been rebuilt more than 30 times at a cost of nearly 100 times the value of the property.[259] Between January 1989 and August 2019, more than 18,000 structures experienced chronic

losses in Ohio, Iowa, Illinois, and Missouri.[260] Repetitive losses are trending upward due to increases in extreme storms and flooding across the region. Some Midwest communities are facing relocation due to projected increases in heavy precipitation and increased flood risk. Managed retreat, or community relocation—moving an entire community out of harm's way—is often discussed as a coastal adaptation measure, but it has applied to the Midwest for decades. Examples, including the town of Valmeyer, Illinois, and the relocation of the Bad River Band of Lake Superior Chippewa in Odanah, Wisconsin, offer lessons on the benefits and drawbacks of flood-induced relocation. Equitable and effective relocation benefits from the coordination of dozens of jurisdictions and substantial funding and often takes years to achieve.[259] These relocation efforts can disrupt social relationships and institutions.[261] As described in Box 20.1, successful and equitable relocation programs require strong community engagement and an open recognition of the multiple drivers of migration, including environmental, economic, and governance conditions.

## *Innovative Finance and Investments*

Recent federal funding from the Infrastructure Investment and Jobs Act is pushing funding to state and local governments to support long-delayed infrastructure upgrades and repairs. As of March 2023, more than $36 billion (in 2022 dollars) in project funding has been invested or announced for infrastructure projects in the Midwest, with an average 15.5% of funding directed toward climate, energy, and environment projects.[262] Along with this infusion of public dollars, the infrastructure investment landscape is changing, with private investment, environmental impact bonds (EIBs), and other financing tools being used in the region. An EIB is a financing tool that allows private investors to provide up-front capital for a pilot project or to scale up an existing project, with the goal of achieving a set of environmental outcomes. Some localities have combined innovative infrastructure approaches, including green infrastructure, with new funding models like EIBs or public–private partnerships. An innovative finance and construction approach being used by the Milwaukee Metropolitan Sewer District (MMSD) is an example of proactive climate adaptation. The MMSD reduced the annual number of combined sewer overflow events from 50–60 in the early 1990s to 2.3 in 2019. Using a community-based public–private partnership, the MMSD is now looking to add an additional 20 million gallons of green stormwater infrastructure (GSI) capture capacity beyond the current capacity of 40 million gallons. The project will allow for public and private investment to support local business and achieve massive green infrastructure benefits by 2026.[263] Other municipalities are implementing GSI, and it is estimated that private investments across Ohio, Wisconsin, Minnesota, Illinois, and Indiana can support more than a billion dollars of GSI.[264] Aside from leveraging private investment, some municipalities are combining funding from multiple public sources, including from different agencies and at different scales of government (federal and state) to fully fund projects. In the case of the Bee Branch Watershed Flood Mitigation Project in Dubuque, Iowa, eight federal and three state funding sources have been applied to the $250 million (dollar year not reported) project.[265]

Careful placement and design of green infrastructure provides benefits beyond flood reduction, such as reducing the urban heat island effect and providing relief to city residents during heatwaves. Green infrastructure such as increased vegetation, stormwater capture systems such as bioswales (vegetative areas that concentrate and move stormwater while filtering for debris and pollution) and detention ponds, and open green spaces can significantly lower temperatures and channel natural airflow, which enhances the cooling effect from the green infrastructure.[266]

## Key Message 24.5

## Managing Extremes Is Necessary to Minimize Impacts on Water Quality and Quantity

Climate-related changes to water quantity and quality are increasing the risks to ecosystem health, adequate food production, surface water and groundwater uses, and recreation (*high confidence*). Projected increases in droughts, floods, and runoff events across the Mississippi River basin and the Great Lakes will adversely impact ecosystems through increased erosion, harmful algal blooms, and expansion of invasive species (*likely*, *high confidence*). Federal and state agencies and nongovernmental organizations are cooperating on adaptation efforts related to streamflow, water quality, and other water issues (*high confidence*).

### *Risk*

Climate change is affecting the quality and quantity of water in the Midwest, as well as management practices related to the health of human and natural systems.[267] Across both the Mississippi River and Great Lakes basins, climate change has impacted streams, rivers, and lakes—all vital to urban, rural, and Tribal communities. Drinking water sources, private wells, and agricultural irrigation sources are at risk. Observed changes in hydrology include increases in the variability of lake levels, evaporation, and water temperatures, along with more intense precipitation,[268] including lake-effect snow, and shorter duration of snow and ice cover. These changes impact food production, businesses, industries, tourism, and recreation. Ecologically sensitive aquatic systems in the Great Lakes are at risk due to changes in lake temperatures and invasive species (KM 24.2).[269]

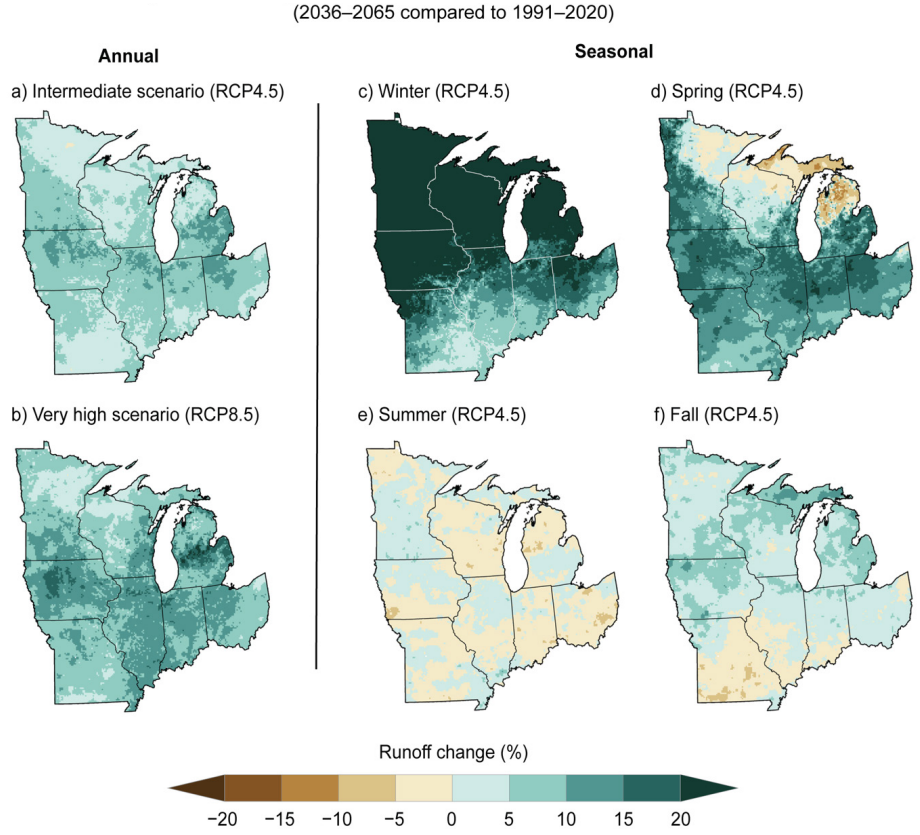
### *Impacts*

#### Mississippi River System

The Ohio River, upper Mississippi River, and lower Missouri River are susceptible to floods and droughts based on projected changes in precipitation, evapotranspiration, and soil moisture (Ch. 4). Precipitation has increased in recent decades (Ch. 2) with more extreme variability and rapid shifts between wet and dry periods (Figure 24.1). Projections across a range of scenarios (low [SSP1-2.6], intermediate [SSP2-4.5], and very high [SSP5-8.5]) indicate future increases in annual precipitation of 0.3% to 1.5% per decade in the eastern Midwest and 0.2% to 0.5% in the western Midwest.[15] Winter and spring precipitation is expected to increase, while summer and autumn precipitation is projected to be more variable.[15]

Cumulative runoff has increased in recent decades[240] and is projected to continue increasing through midcentury (Figure 24.11), leading to increased riverine flooding in the Ohio, upper Mississippi, and parts of the Missouri River basins. Prolonged periods of increased cumulative runoff have adversely impacted ecosystems and commerce and are projected to continue to do so.[240] Observed decreases in the length of winter have reduced snowfall across the Midwest,[270] with negative impacts for snow-dependent winter tourism for the Midwest and Great Lakes (KM 24.2).[178] By the end of the century, projections indicate reductions in snowstorm frequency and size and snow-water equivalent totals;[271] shorter snow seasons; and fewer intense snowfall events.[272]

## Projected Changes in Cumulative Seasonal and Annual Runoff




**Projected changes in cumulative local runoff will lead to increased flooding susceptibility in winter and spring, with increased flash drought potential in summer.**

**Figure 24.11.** The maps show projected changes in the annual approximate cumulative gridded local runoff generation (referred to as cumulative runoff) for intermediate (RCP4.5) and very high (RCP8.5) scenarios (**a**, **b**) and seasonal approximate cumulative runoff for an intermediate (RCP4.5) scenario (**c**–**f**). The cumulative runoff is defined as the gridded cell-by-cell ability of the landscape to generate excess water for potential downstream river runoff using the Variable Infiltration Capacity (VIC) land-surface model. The cumulative runoff was developed using Coupled Model Intercomparison Project Phase 5–modeled scenarios and the VIC hydrology model. Cumulative runoff is projected to increase annually across the Midwest between 2036 and 2065 compared to 1991–2020 (shown in percent changes). Cumulative runoff increases are expected throughout the region in winter and across all but the northern Great Lakes in spring and southern Midwest in fall. Summer cumulative runoff is projected to be more variable. The result of the projected increases (and in summer, both increases and decreases) in cumulative runoff will be increased stresses to ecosystems, the built environment, natural and water resources, and agriculture. Figure credit: NOAA NWS, NOAA NCEI, and CISESS NC.

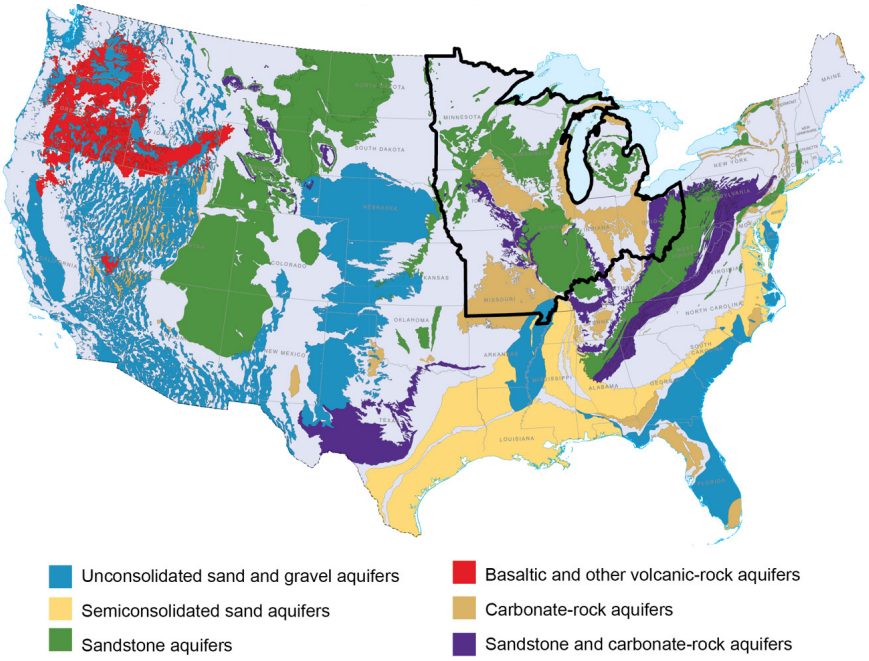
Midwest droughts develop in response to precipitation deficits or extremely high temperatures and evapotranspiration (KM 4.1). In recent decades, evapotranspiration has become, and is expected to continue to be, the dominant driver of drought,[273,274] especially across the eastern Midwest.[275] Precipitation deficiencies remain the primary driver of increased drought in the southwestern Midwest.[276]

Groundwater storage is important for water resource management, including wastewater permitting, water supply, and fisheries. Groundwater recharge is projected to be variable in the Midwest,[277] with water imbalances[28] resulting from precipitation and evapotranspiration changes. Failure of private wells is expected to increase during droughts as water tables drop with increased irrigation and water usage.

Vulnerability to water shortages and water quality depend, in part, on the primary source for water use and drinking water for any given location (aquifers/deep groundwater versus surface/shallow groundwater;

Figure 24.12). Thus, drought occurrences will have different impacts based on the source. For surface water, decreases in summer runoff (Figure 24.11) can reduce water quality and streamflows.[278] Aquifers, on the other hand, are more resilient to rapid hydrological transitions but are still impacted by longer-term drought conditions.[278] Precipitation is projected to increase in all seasons, while runoff is projected to increase in the cool season but become more variable in the warm season (Figure 24.11). The combination of warming temperatures and more variable summer runoff suggests an increased risk of drought for people, crops, livestock, and ecosystems across the region.[240] At the same time, increased precipitation and runoff events (Figure 24.11; KM 4.1) are expected to increase nuisance flooding (KM. 24.4) and sewage spills and resulting odor releases, as well as deteriorate water quality due to increased uncontrolled discharges. Stormwater runoff increases are expected to harm aging infrastructure and lead to higher costs for new systems (KM 24.4). Thus, urban and rural managers are implementing best practices for water quality across diverse landscapes, from agriculture (Figure 24.4) to forests (Figure 24.5) and the built environment (KM 24.4).[164]

## Map of US Aquifers




**Vulnerability to disruptions in water quality and quantity varies by location, depending on the primary source of water for drinking and other uses.**

**Figure 24.12.** The USGS Ground Water Atlas of the United States provides a complete summary of the Nation's groundwater resources and includes the location, geography, geology, and hydrologic characteristics of the major US aquifers. Surface water and groundwater (aquifers) are the primary sources of water in the Midwest and Great Lakes. The areas highlighted in color represent groundwater aquifers, while areas in gray represent surface water as the main source. The black boundary outlines the Midwest region. Changes in rainfall and runoff patterns impact water availability and water tables differently across the Midwest, depending on whether the main source of water is surface- or aquifer-based. For more information on aquifers outside the contiguous US, visit the USGS Ground Water Atlas of the United States and Principal Aquifers of the United States. Adapted from USGS 2021.[279]

Harmful algal blooms (HABs) and their impacts to water quality, food production, recreation, tourism, and ecosystems continue to be a major concern across parts of the Midwest. Observed increases in precipitation[15,268] are resulting in, and are projected to continue to result in, increases of sediment and nutrient loads in the Mississippi River system. However, research has been inconsistent about whether HAB severity and magnitude in the Midwest have been increasing, remaining constant, or decreasing.[280,281]

## Great Lakes

The Great Lakes are the largest freshwater ecosystem on Earth[282] and are among the fastest-warming lakes in the world.[283] The Great Lakes Water Quality Agreement between the United States and Canada established a suite of nine indicators to assess the ecosystem health of the Great Lakes (Table 24.1). While efforts to restore and protect the Great Lakes are ongoing, this ecosystem is at risk from shifts in seasonality (changes in the timing of the formation and destruction of temperature stratification) and from changes in ice cover, maximum summer temperatures, and oxygen levels, which have significant impacts on fisheries and habitats in the lakes.[282] Invasive species and threats to biodiversity are the greatest concerns of the Great Lakes.[282] Aquatic invasive species (KM 24.2) can degrade water quality by decreasing water clarity, concentrating toxins, and altering nutrient flows within the food web. Great Lakes water quality across a wide range of metrics currently ranges from fair to good.[282]

**Table 24.1. State of the Great Lakes 2022 Assessment**

CAPTION: The EPA and Environment and Climate Change Canada work jointly to meet the mission of the Great Lakes Water Quality Agreement. As part of this effort, the State of the Great Lakes Report is released every three years. The following table details the state of the Great Lakes using 10 Indicators. The assessments are basin-wide and typically vary between lakes. The metrics listed are synthesized to determine the status and trends of each indicator. The definitions for "poor," "fair," and "good" are quantitative, vary between indicators, and are documented in the report (ECCC and EPA, 2022).[282] Status assessments are not provided for the climate trends indicators. Adapted from ECCC and EPA 2022.[282]

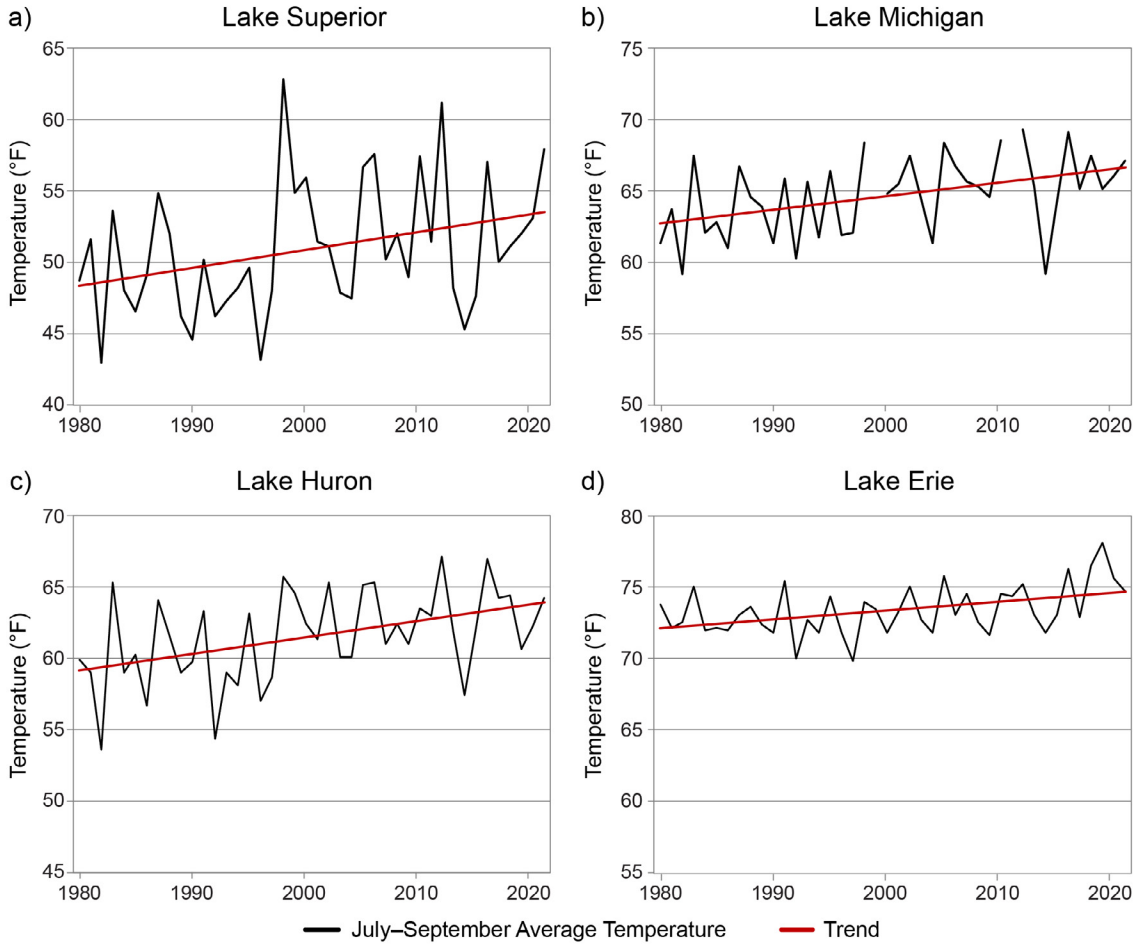
| Great Lakes Indicator | Metric | Status | Trend |
|---|---|---|---|
| Drinking Water | US/Canadian drinking water standards (microbial, radiological, chemical) | Good | Unchanging |
| Beaches | *E. coli* assays | Good | Unchanging–improving |
| Fish Consumption | Polychlorinated biphenyls [PCBs] and mercury in fish flesh | Fair | Improving |
| Toxic Chemicals | Concentrations of compounds (PCBs, mercury, polybrominated diphenyl ethers, and others) in sediment, water, whole fish, and herring gull eggs | Fair | Unchanging–improving |
| Habitat and Species | Overall health and habitat conditions and availability of invertebrates, fish, amphibians, birds, plants, connectivity | Fair | Unchanging |
| Nutrients and Algae | Nutrient concentration, harmful algal blooms, *Cladophora* | Fair | Unchanging |
| Invasive Species | Rate of introduction | Good | Unchanging |
| Invasive Species | Aquatic invasive species impacts | Poor | Deteriorating–unchanging |
| Groundwater | Chloride/nitrate concentrations | Good | Undetermined |
| Watershed Impacts | Forest and land cover, hardened shorelines, tributary water quality, human population | Fair | Unchanging |
| Climate Trends | Lake levels | N/A | Unchanging–increasing |
| Climate Trends | Surface water temperature | N/A | Increasing |
| Climate Trends | Ice cover | N/A | Decreasing |

The Great Lakes have witnessed significant water-level variability over the last several decades, with low water levels from 1998 to 2013 and high-water levels since 2015. This variability is due in part to changes in the seasonality and intensity of precipitation (including lake-effect snow), warmer lake temperatures, lake evaporation, and loss of ice cover.[284] The twin stressors of increases in precipitation and air temperature result in increased interannual variability in lake levels.[285] However, the complex interactions between lakes, land, and atmosphere make the system difficult to model, so that long-term projections of net basin supply and lake levels have high uncertainty.[6] These climate changes impede current water management practices for the Great Lakes, which are similar to those elsewhere in the Midwest, with the added challenge of transboundary water agreements with Canada (Ch. 4). For example, low water levels limit power production from hydropower facilities and pose risks to shipping[286] and ports (KM 24.4), while high water levels lead to shoreline erosion, loss of coastal habitat[287] and flooded communities. Shorelines are also at risk from high-wind events during high-water-level episodes.[288]

Great Lakes water and air temperatures have been rising since 1980[282] (Figure 24.13). Summer surface water temperatures recorded by offshore buoys have shown nearly uniform increases across the upper Great Lakes (Superior, Michigan, and Huron). Lake Erie shows slower warming rates, while there are not enough data from Ontario to make a determination. Increases in lake surface temperatures are expected on all five lakes.[289] Although uncertainty remains on the seasonal and spatial variability, increased temperatures are expected to result in loss of suitable fish habitat.[290] How the surface warming will affect the rest of the water column and the overall impact on the ecosystem is not as well characterized. Coupled with increasing water temperatures is a decrease in winter ice cover,[291] which is observed on all five lakes and has cascading impacts on ecosystems and culture (KM 24.2; Figure 24.6).

## Great Lakes Summer Surface Water Temperature Trends

(1980–2021)




**Summer surface water temperatures have been increasing for Lakes Superior, Michigan, Huron, and Erie since the late 1970s.**

**Figure 24.13.** The graphs show summer (July–September) surface water temperatures for the period 1980–2021 observed from buoys in the offshore waters of Lakes Superior, Michigan, Huron, and Erie. The upper lakes (Superior, Michigan, and Huron; **a**–**c**) show similar trends toward warmer temperatures against a background of strong interannual variability, while Lake Erie (**d**) shows a weaker but still positive trend. To facilitate comparison of trends, a temperature range of 25°F is used for the vertical axis on all four charts, with actual temperatures varying across the different lakes. Figure credit: University of Minnesota Duluth, NOAA NCEI, and CISESS NC

HABs occurring in portions of all five of the Great Lakes, including western Lake Erie and parts of Lake Superior, are affecting people through poor water quality and advisories against swimming and beachgoing. HABs also negatively impact habitats and fisheries. Projected increases in cumulative annual runoff (Figure 24.11), which elevate the risk of nonpoint-source pollution (natural and human-made pollutants that are carried from many sources by precipitation and runoff) and warming trends across the Great Lakes (Figure 24.13), are expected to promote the growth of HABs through midcentury. Although the direction of change of HABs across the Midwest is inconsistent,[280,281] recent trends in western Lake Erie show a significant increase in the extent and severity of HAB events over the last 20 years.[282]

## Managing Hydrologic Complexity and Extremes

Federal, state, and local governments and institutions are working with communities on initiatives to adapt to and/or lessen the impacts of climate change. For example, the US Army Corps of Engineers has partnered with federal agencies, nongovernmental organizations, and institutions on the Ohio River Basin Climate Change project.[240] The goal was to create a comprehensive plan to address changing streamflows and identify adaptations needed to deal with water quantity, quality, and management challenges related to regulations, recreation, navigation, and aquatic habitats (e.g., fisheries). A similar study with NOAA and the University of Minnesota for the upper Mississippi River basin kicked off in 2022. Additionally, a number of climate resilience partnerships throughout the Midwest and Great Lakes have been completed.[292]

As part of the National Integrated Drought Information System, the Midwest Drought Early Warning System was established in 2016 to advance drought monitoring, forecasting, and preparedness in the region and to improve regional capacity to respond to drought.[293,294]

To adapt to extreme runoff, strong private and public partnerships can help formulate best management practices for reducing nutrient and sediment loads into streams and rivers. NOAA is accomplishing this through the Runoff Risk Decision Support project.[295] NOAA is working with state departments of agriculture in parts of the Midwest and Great Lakes, including Minnesota, Wisconsin, Michigan, and Ohio, as well as New York. The NOAA Runoff Risk Decision Support tool provides the agriculture community with timely forecast information on when to apply fertilizers. Most fertilizer applications are executed in the Midwest and Great Lakes during the winter into spring just before planting season, which is also peak runoff season. A significant percentage of total nutrient and sediment losses typically occur from a small number of runoff events each year.[296,297] The information provided by this tool allows farmers to make better-informed decisions on when to apply manure and fertilizer. The correct application of manure and fertilizer will reduce the risk of chemicals entering into river systems. The reduction of excess chemicals, including nitrogen and phosphorus, entering into waterways is important, since high nutrient and sediment loads contribute to impactful environmental HAB and hypoxia (low oxygen level) events.[297] The Mississippi River/Gulf of Mexico Hypoxia Task Force and the US/Canada Great Lakes Water Quality Agreement highlight the need for nutrient load reductions in the Mississippi and Great Lakes watershed systems, due to increasing impacts on both the public health system and ecosystems.[298]

# Traceable Accounts

## *Process Description*

The Midwest chapter authors were identified and recruited in August and September of 2021. The goal was to construct the team with at least one author from each of the Midwest states, with attention to geography, interconnected systems, level of expertise, gender, and diversity. The selection of authors was based on Federal Registry Notice comments, USGCRP (US Global Change Research Program) Research Gaps Summary for the Midwest, and author nominations, as well as discussions and nominations by the chapter lead, coordinating lead author, agency chapter lead, and National Coordination Office point of contact. Authors were added iteratively, with those who accepted early providing additional suggestions for subsequent nominations. All but two of the invited authors agreed to participate.

Regular virtual meetings were held during the fall of 2021, with the Zero Order Draft finalized in December 2021. The Midwest chapter hosted a virtual public engagement workshop on January 24, 2022. The key topics selected were well received, with ample discussion and feedback. Authors considered the comments along with inputs provided in the public call for technical material and incorporated the available recent scientific literature in developing the Key Messages for the First Order Draft. Author consensus was built through routine meetings and based on feedback from the NOAA Technical Support Unit (TSU); federal agencies; the National Academies of Sciences, Engineering, and Medicine; and public comment review periods. This iterative process occurred between the Second and Fourth Order Drafts, from the winter of 2022 to the spring of 2023.

## Key Message 24.1

## Climate-Smart Practices May Offset Complex Climate Interactions in Agriculture

### Description of Evidence Base

There is strong evidence that increasing extreme precipitation events, changing seasonality, and rapid transitions between hydrologic conditions are negatively impacting soil conditions and challenging traditional row crop agricultural production in the Midwest, with uncertainty remaining due to local climate influences and limitations with downscaled climate data.[12,18] Studies link the loss of soil and applied nutrients to increasing rainfall, with cascading impacts including financial loss and increased water quality issues. Numerous studies point to future decreases in corn production, in combination with episodic drought, and increases in the production of some crops like wheat due to cooler-season changes including warmer springs and greater rainfall (e.g., Li et al. 2019[2]). Impacts on animal agriculture in the region remain an understudied topic, although some studies have shown impacts are already occurring (e.g., Crist et al. 2020[51]). Many of these projected impact studies rely heavily on a very high scenario (e.g., RCP8.5), which limits the assessment of the full range of uncertainty.

Reports and studies strongly demonstrate the economic importance of specialty crops to the Midwest and their vulnerability to climate change.[56] Most studies to date focus on the impact of spring-freeze injury, although a limited number of studies address other impacts such as excessive moisture, disease, and pest pressure. Evidence suggests a wide range of future outcomes to specialty crops based on species and location of cropping systems within the Midwest. Studies on the direct impacts of rising temperature and altered precipitation patterns on specialty crops across the Midwest remain limited. The evidence base for the impacts of climate change on important pollinators and insect species distributions is growing.

An increasing number of studies address agriculture's impact on climate, particularly the intensification of cropping systems and potential impacts from increased irrigation.[46] Impacts on atmospheric moisture and feedback loops within the system are ongoing.

Studies have linked, at least in part, climate change to crop insurance losses across the US and the Midwest.[75] These losses are related to drought and excess moisture. Building resilience to these hazards is part of a climate-smart approach. Studies to evaluate specific benefits and other impacts from varying climate-smart techniques are evolving.

## Major Uncertainties and Research Gaps

Current climate trends are, in some ways, counter to projected climate conditions and differ from other regions of the country. For example, summer daytime warming trends (daily maxima) and drought are not occurring as projected by previous model simulations. Historical changes have been much more seasonally dependent, with the largest increases in temperature occurring during the cooler seasons rather than the summer. A high degree of uncertainty also exists in individual model-projected changes in the intensity and seasonality of future precipitation, as well as the attribution of these complexities to anthropogenic sources. While model consensus strongly points to overall increases in annual temperature, additional investigations on the interactions between agriculture and its impact on climate in the region would help resolve seasonal discrepancies. Reductions in model and scenario uncertainty would improve local impact assessments and decision-making.

More detailed information about projected changes in other climate parameters (e.g., vapor pressure deficit, soil moisture, extremes, and severe events) and impacts on specific crops would be needed for a broader understanding of the potential impacts on agricultural production and increased confidence in the findings. This includes studies beyond corn, soybean, and wheat, including other cash and specialty crops (e.g., apples, pumpkins, cucumbers). Detailed information on secondary climate change impacts (i.e., increased insect, disease, and weed pressure on production) is less well understood as well. Analyses of historical changes in the distributions of agricultural pests are limited, as are model projections of their future distributions.

With respect to social equity and justice concerns for agriculture in the Midwest, identifying and increasing engagement with BIPOC (Black, Indigenous, and People of Color) communities and low-resourced communities across the Midwest could increase the sharing of information and bring resources to these communities to enhance their climate adaptation and mitigation activities already underway. This would lead to a more informed and full assessment of the impacts, adaptation, and mitigation agricultural activities already taking place within these communities. There have been recent federal investments, for example, that have infused support into National Institute of Food and Agriculture programs that bring social and physical scientists together to help fill in this knowledge gap. Work from these new projects could be sought for future National Climate Assessment reports.

Research activities on the ability for climate-smart practices to help agriculture adapt to changing climate conditions and lessen future issues are increasing. However, further investigation of the potential trade-offs between strategies and a diverse set of outcomes based on crop, cover, soil type, and local changes in climate would be needed to increase confidence in their use and whether they reach desired outcomes. Research does support some climate-smart practices, but widespread implementation and interaction of various practices is poorly understood.

### Description of Confidence and Likelihood

Based on numerous studies and converging evidence, there is *high confidence* and it is *likely* that climate change is negatively impacting agriculture in various ways. Examinations of historical extreme precipitation events and rapid transitions between hydrological states through novel analysis techniques show that these phenomena are *likely* increasing in number, and projections show that they are *likely* to continue throughout the 21st century. The team focused on the challenges, including poor field conditions and potential crop losses, that are *likely* to accompany these changes in the hydrological conditions. Although crop impacts are *likely* based on similar results across scales and methods, uncertainty in specific impacts by species (crop, insect, etc.) leads to *medium confidence* in future outcomes of row and, especially, specialty crops. Other *likely* changes, including snowmelt timing and extreme precipitation events in spring, will lead to additional impacts on animal agriculture in the region, and attention was given to dairy production as a major component of animal agriculture in the Midwest (*high confidence*). Climate-smart adaptation techniques provide a potential path toward environmental and economic sustainability, but the limited converging evidence and adoption to date lead to overall *medium confidence* in their ability to mitigate future agricultural challenges.

## Key Message 24.2

## Adaptation May Ease Disruptions to Ecosystems and Their Services

### Description of Evidence Base

Strong convergent evidence from many sources in the published and gray literature shows that climate change is impacting natural resources in the Midwest and that these impacts will further intensify with advancing climatic change. However, the amount of evidence varies by ecosystem, the particular type of environmental change, and geographic location within the Midwest.

Strong convergent evidence from published studies shows that Midwestern aquatic ecosystems are responding to increasing temperatures and to changes in extreme weather.[97,99] There is a moderate amount of evidence demonstrating that these systems are responding to increasing precipitation. Several studies show that flooding and drought pose increasing risk to aquatic ecosystems, specifically by altering structure and community dynamics.

The evidence from published studies demonstrating that terrestrial ecosystems are being altered by climate change is strong overall (e.g., Contosta et al. 2019[133]), although the amount of evidence for any given ecosystem type being affected by any given environmental change is variable. Evidence supports the finding that impacts have been more pronounced in more northerly parts of the Midwest. Overall, there is unequivocal evidence that Midwestern ecosystems have been and will continue to be affected by landscape change, and many studies link changes in the functioning of these systems to rising temperatures and reduced snow and ice cover.[133,151] There is strong evidence that these climatic factors have been changing in the Midwest.

### Major Uncertainties and Research Gaps

Much of the uncertainty concerning Midwestern natural resource responses to climate change is linked to the varying responses across species, ecosystems, and geographic location. Many species and some ecosystems are subjects of few or no direct studies; some variables have been studied in only one location within the Midwest; and species interact in complex ways that could potentially lessen or reverse direct effects of climate change in some cases—all of which increase the uncertainties of projected climate change responses.

Assessing projected responses to climate change can be challenging because of scale mismatches with climate model output. For example, streams are much smaller than climate model grids and as such require offline downscaling. Although this has been done, it has not covered the breadth of Shared Socioeconomic Pathway (SSP) scenarios.

There is significant uncertainty concerning how widely human communities are adapting their cultural practices to climate change and whether adaptation strategies have documented benefits. Case studies are available,[145] but more information is needed across the full spectrum of Midwestern communities.

### Description of Confidence and Likelihood

Broad evidence from published studies indicates it is *likely* that climate change is impacting natural resources in the Midwest (*high confidence*). Published studies show that flooding and drought *likely* pose increasing risk to aquatic ecosystems by altering structure and community dynamics, although agreement on the precise magnitudes of effects is less clear (*medium confidence*). Numerous studies show that rising temperatures, altered winter conditions, and landscape changes are *very likely* altering terrestrial ecosystems and limiting their adaptive capacity (*high confidence*). This is particularly pronounced in northern ecosystems. Emerging evidence shows that losses of ecosystem services are undermining human well-being, causing the loss of economic, cultural, and health benefits (*medium confidence*). Owing to the site- and ecosystem-specific nature of the evidence, it is difficult to make broad generalizations across the Midwest. People are adapting management and cultural practices in response to climate change, particularly for inland lakes and forest systems; many of these practices have co-benefits for ecosystem services, including mitigation of climatic changes (*low confidence*). The authors assess with *low confidence* because of noted knowledge gaps across the Midwest concerning both community actions and documented responses.

## Key Message 24.3

## Climate Adaptation and Mitigation Strategies Improve Individual and Community Health

### Description of Evidence Base

There is strong evidence that increasing temperatures and changes in historical precipitation patterns are occurring across the Midwest and will *likely* continue through the end of the century. The level of air contaminants, such as particulate matter, ozone, and pollen, are positively associated with rising temperatures, and there are numerous studies describing the link between exposure to these contaminants and increased morbidity and mortality.[186,187]

Exposure to climate-related events, such as extreme heat and flooding, has been shown to impact the health and well-being of Midwest communities, as well as degrade social and environmental determinants of health.[178,179] The occurrence of extreme heat and precipitation events is projected to rise across the Midwest. However, there are few in-depth qualitative assessments that capture and report person- or community-specific information from those impacted, particularly the short- and long-term effects of experiencing a climate-related hazard. Increases in intense rainfall have been linked to increased exposure to waterborne contaminants in both public and private drinking water systems in the Midwest.[201,204] Studies using climate projection data have shown that climate-related seasonal precipitation changes will increase the rates of gastrointestinal illness in children.[203]

There is strong evidence that rising temperatures are contributing to the expansion of disease-carrying vectors like ticks and mosquitoes into and across the Midwest.[207] Modeling using climate projections

predicts that the range of many established and newly invasive species will increase throughout the century, increasing the risk of various zoonotic diseases like Lyme disease and West Nile virus.[208]

Climate change is associated with negative impacts on mental health.[211] However, there are few studies, particularly based on Midwest populations, that link robust measures of climate change or climate-related events with clinically validated psychiatric diagnoses.

There is a substantial increase in the number of climate assessments conducted for Midwest states and cities that emphasize the need to address systemic injustice and historical racism and prioritize equity in climate resilience decision-making.[32,299,300] Many of these reports also acknowledge the need to involve disproportionately impacted communities in the design and implementation of resilience strategies. These assessments are not part of the peer-reviewed literature and thus were not considered as part of the evidence base for this section. However, it is notable that many Midwest climate assessments have not only included but also prioritized these issues as part of their climate resilience planning.

## Major Uncertainties and Research Gaps

While there are many studies linking climate change to impacts on health and community well-being, only a small number of these studies have been conducted directly or solely on Midwest populations. Furthermore, to capture the breadth of potential impacts, these studies could consider a range of scenarios, not just the highest or worst-case scenarios.

There is a gap in research characterizing how climate-related health impacts differ based on local population-specific characteristics and shared realities, particularly across the urban–rural gradient and multiple Tribal Nations and as a result of increasing immigration. This is particularly true for specific health outcomes (e.g., mental health) and health determinants (e.g., livelihood). Such information would be useful for developing targeted, effective intervention strategies that address existing inequities and historical racism.

The literature currently lacks studies specific to the Midwest that attempt to quantify the cost burden associated with climate impacts on health and key health determinants like livelihood or housing security. Thus, there is uncertainty about how much climate change impacts are costing Midwest communities in terms of injury, disease, job loss, property damage, healthcare utilization, and more.

Certain emerging topics for climate and health in the Midwest, including climate-driven migration and concerns for people with disabilities, were not covered due to a lack of literature specific to the Midwest region. Thus, it is uncertain what the attending health impacts may be related to these topics and how they may be distributed throughout a community.

## Description of Confidence and Likelihood

There is *high confidence* and it is *very likely* that climate change will impact the health and well-being of individuals and communities in the Midwest across a wide range of exposure pathways. Literature shows that these pathways include extreme events, such as flooding, drought, heatwaves, and wildfires, that all pose an increasing risk to physical and mental health by direct exposure. Studies show that indirect exposure through degrading air and drinking water quality threatens livelihoods and strains essential health and emergency-related services. An individual's exposure and sensitivity to climate change is *very likely* influenced by preexisting health conditions, income, race and ethnicity, age, and access to resources (*high confidence*). Evidence illustrates that health disparities tied to racism and income inequality are *likely* linked to an inequitable distribution of climate-related health outcomes. Actions and investments to reduce climate-related health and community impacts can yield multiple health benefits while helping to advance more equitable climate adaptation (*high confidence*).

## Key Message 24.4

## Green Infrastructure and Investment Solutions Can Address Costly Climate Change Impacts

### Description of Evidence Base

Based on numerous independent analyses, much of the infrastructure of the Midwest is aging, and repairing this infrastructure will come at a significant cost (e.g., American Society of Civil Engineers Report Card for America's Infrastructure).[248] These costs require new forms of financing, data, and expertise, much of which is just emerging. The infrastructure deficit in the Midwest is articulated through academic literature and practitioner resources and research,[236,248] all demonstrating that the infrastructure of the Midwest is aging and that repairing it will come at a significant cost. These costs require new forms of financing, data, and expertise, much of which are just emerging.[236] There is strong evidence showing that increasing storm damages to infrastructure across the Midwest disproportionately impact people with low income and BIPOC populations.[258] Numerous studies of social vulnerability and adaptive capacity demonstrate that individuals with lower vulnerability and higher adaptive capacity are better able to prepare for and recover from disaster.

### Major Uncertainties and Research Gaps

Storm damages not captured through disaster declarations are difficult to identify, and midsize disasters are difficult to quantify. One method for quantifying these midsize disasters could be to report on the total times states in the Midwest declare a state of emergency in response to a weather- or climate-related event. There is a gap in aggregated and standardized reporting of state-declared disaster events and related losses. Another approach could be to calculate insurance losses as reported by private insurance companies with holdings in the region. State-level data and private insurance datasets are accessible but require analysis and synthesis to be usable by decision-makers. The US Billion-Dollar Weather and Climate Disasters report, developed by NOAA's National Centers for Environmental Information, has become a common way to understand the increasing cost incurred by climate change and related extreme events. However, many smaller-scale yet damaging storm events occur annually and lead to damage or destroyed infrastructure, loss of life, and harm to the health and well-being of people in the Midwest. One measure of these events is through the National Flood Insurance Program database. Tracking these events and the related economic impact could enable more effective and equitable distribution of resources before and following extreme storms.

Climate migration is an area of uncertainty, yet information is highly sought within academic and public spheres. Literature and resources on community relocation within the region exist, but literature and evidence on climate-induced migration of people moving into the region is not currently available.

### Description of Confidence and Likelihood

There is strong evidence that climate change *likely* threatens built infrastructure, especially if a heavy dependence on conventional road transportation continues. Uncertainty about the modes of transportation that will exist in the future and uncertain trends toward electrification result in an assignment of *medium confidence*. More certain are the impacts from increased precipitation extremes and transitions between wet and dry conditions on riverine and Great Lakes environments (*likely*, *high confidence*). The emergence of new investments offers alternative methods toward development, but volatility in the economy leaves some uncertainty whether more communities and local businesses will embrace these tools (*medium confidence*).

## Key Message 24.5

## Managing Extremes Is Necessary to Minimize Impacts on Water Quality and Quantity

### Description of Evidence Base

There is strong evidence that the Midwest and Great Lakes water is and will continue to be impacted by climate change, with associated adverse effects for both human society and ecosystems.[267] The evidence for change is supported by the trends in temperature, precipitation, runoff, and evapotranspiration.[268] Further, reasonably good climate-based scenario model performance in the past provides confidence in those predictions going forward.

The evidence and research were more consistent for water quantity and water management than for water quality.[280,281] This is due, in part, to the more complex nature of water quality. The biggest areas for lack of agreement were in harmful algal blooms (HABs) and how global climate scenario-based models deal with the regional representation of the Great Lakes.

### Major Uncertainties and Research Gaps

The lack of robust model simulations of how the Great Lakes physically operate is a major gap and uncertainty. Climate processes in the Great Lakes region are difficult to simulate due to the complexity of lake–land–atmosphere interactions.[6] Even the most sophisticated climate models for the Great Lakes region have deficient physical representations of the key hydrological components that make up a lake's net basin supply (i.e., precipitation, evaporation, and runoff).[6] Therefore, high levels of uncertainty are associated with future lake-level projections that are based on simulated changes to these hydrological components. However, higher variability in future water levels is anticipated, which will impact the entire ecosystem (KM 24.2), ports (KM 24.4), and coastlines.[284,301] Better physical representation of the Great Lakes would enhance confidence in how increases in the water temperatures of the lakes (both surface and deep lake) could impact the ecosystem.

HAB research across the Midwest and Great Lakes is conflicting and limited.[280,281] While research has been more conclusive in the Great Lakes with increasing HAB severity, research has been inconclusive in the Midwest as to whether HAB severity has been increasing, remaining constant, or decreasing. Connections to agricultural tiling and septic systems and their impacts on water bodies are additional knowledge and data gaps.

Temperature, precipitation, and runoff research is much more comprehensive in the Midwest than streamflow research.[268] There is limited available work on large basin–scale streamflow to assess climate impacts. The Ohio River Basin Climate Change project, by the US Army Corps of Engineers and NOAA,[240] is one of the US's largest and most comprehensive climate change–related projects on water quantity, quality, and management for streamflows on medium- to larger-scale systems. A similar Midwest project by NOAA's North Central River Forecast Center and the University of Minnesota is underway for the upper Mississippi River basin. More large-scale hydrologic projects, including in the Missouri River basin and Great Lakes, would aid in understanding large-scale streamflow changes and projected impacts. The absence of more such projects limits the ability to have higher confidence in some areas of water quantity, quality, and management. Combining Coupled Model Intercomparison Project Phase 5 with the Variable Infiltration Capacity hydrology modeling is a step in the right direction.

## Description of Confidence and Likelihood

Confidence and likelihood were assigned based on the consistency of the information in trends and research combined with strengths and weaknesses in the climate scenario models. For the Midwest and Great Lakes, there is consistent information to support *high confidence* for air temperatures, precipitation, and runoff trends and projections and the impacts to water quantity, water quality, water management practices, ecosystem health, food production, and recreation.[15] Based on literature and projections, it is *likely* and there is *high confidence* that increases in runoff (in all seasons but summer, where some decreases are projected), drought, and flooding will adversely affect ecosystems through increased erosion and the expansion of invasive species. This applies to enhanced erosion and expansion of invasive species. For harmful algal blooms (HABs), the literature and projections support *high confidence* for continued HABs in the Great Lakes. For the Midwest, confidence is lower that increased temperatures and precipitation and runoff will continue to lead to variable changes in HAB events (increasing, decreasing, or remaining unchanged). This will *likely* result in continued adverse impacts to water quality and ecosystems. There are numerous examples where federal and state agencies along with nongovernmental organizations are collaborating on adaptation efforts related to water in the Midwest (*high confidence*).

# References


1. U.S. Census Bureau, 2020: Explore Census Data. U.S. Department of Commerce, U.S. Census Bureau, accessed May 5, 2023. https://data.census.gov/

2. Li, Y., K. Guan, G.D. Schnitkey, E. DeLucia, and B. Peng, 2019: Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. *Global Change Biology*, **25** (7), 2325–2337. https://doi.org/10.1111/gcb.14628

3. Srivastava, A., O. Yetemen, N. Kumari, and P.M. Saco, 2019: Aspect-controlled spatial and temporal soil moisture patterns across three different latitudes. In: *Proceedings of the 23rd International Congress on Modelling and Simulation*. Canberra, ACT, Australia, 1–6 December 2019, 979–985. https://doi.org/10.36334/modsim.2019.k6.srivastava

4. Sharma, S., D.C. Richardson, R.I. Woolway, M.A. Imrit, D. Bouffard, K. Blagrave, J. Daly, A. Filazzola, N. Granin, J. Korhonen, J. Magnuson, W. Marszelewski, S.-I.S. Matsuzaki, W. Perry, D.M. Robertson, L.G. Rudstam, G.A. Weyhenmeyer, and H. Yao, 2021: Loss of ice cover, shifting phenology, and more extreme events in Northern Hemisphere lakes. *Journal of Geophysical Research: Biogeosciences*, **126** (10), e2021JG006348. https://doi.org/10.1029/2021jg006348

5. Schlinger, C., O. Conroy-Ben, C. Cooley, N. Cooley, M. Cruz, D. Dotson, J. Doyle, M.J. Eggers, P. Hardison, M. Hatch, C. Hogue, K. Jacobson Hedin, C. Jones, K. Lanphier, D. Marks-Marino, D. Mosley, F. Olsen Jr., and M. Peacock, 2021: Ch. 4.2. Water. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 98–141. http://nau.edu/stacc2021

6. Briley, L.J., R.B. Rood, and M. Notaro, 2021: Large lakes in climate models: A Great Lakes case study on the usability of CMIP5. *Journal of Great Lakes Research*, **47** (2), 405–418. https://doi.org/10.1016/j.jglr.2021.01.010

7. FAO, 2022: FAOSTAT. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#home

8. NASS, 2022: Quarterly Hogs and Pigs Inventory–United States. U.S. Department of Agriculture, National Agricultural Statistics Service. https://usda.library.cornell.edu/concern/publications/rj430453j?locale=en

9. Angel, J.R., M. Markus, K.A. Wang, B.M. Kerschner, and S. Singh, 2020: Precipitation frequency study for Illinois. *Illinois State Water Survey Bulletin*, **75**, 130. https://hdl.handle.net/2142/106653

10. Baule, W.J., J.A. Andresen, and J.A. Winkler, 2022: Trends in quality controlled precipitation indicators in the United States Midwest and Great Lakes region. *Frontiers in Water*, **4**, 817342. https://doi.org/10.3389/frwa.2022.817342

11. Hayhoe, K., D.J. Wuebbles, D.R. Easterling, D.W. Fahey, S. Doherty, J. Kossin, W. Sweet, R. Vose, and M. Wehner, 2018: Ch. 2. Our changing climate. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 72–144. https://doi.org/10.7930/nca4.2018.ch2

12. Wilson, A.B., A. Avila-Diaz, L.F. Oliveira, C.F. Zuluaga, and B. Mark, 2022: Climate extremes and their impacts on agriculture across the eastern Corn Belt region of the U.S. *Weather and Climate Extremes*, **37**, 100467. https://doi.org/10.1016/j.wace.2022.100467

13. Guo, R., C. Deser, L. Terray, and F. Lehner, 2019: Human influence on winter precipitation trends (1921–2015) over North America and Eurasia revealed by dynamical adjustment. *Geophysical Research Letters*, **46** (6), 3426–3434. https://doi.org/10.1029/2018gl081316

14. Knutson, T.R. and F. Zeng, 2018: Model assessment of observed precipitation trends over land regions: Detectable human influences and possible low bias in model trends. *Journal of Climate*, **31** (12), 4617–4637. https://doi.org/10.1175/jcli-d-17-0672.1

15. Almazroui, M., M.N. Islam, F. Saeed, S. Saeed, M. Ismail, M.A. Ehsan, I. Diallo, E. O'Brien, M. Ashfaq, D. Martínez-Castro, T. Cavazos, R. Cerezo-Mota, M.K. Tippett, W.J. Gutowski, E.J. Alfaro, H.G. Hidalgo, A. Vichot-Llano, J.D. Campbell, S. Kamil, I.U. Rashid, M.B. Sylla, T. Stephenson, M. Taylor, and M. Barlow, 2021: Projected changes in temperature and precipitation over the United States, Central America, and the Caribbean in CMIP6 GCMs. *Earth Systems and Environment*, **5** (1), 1–24. https://doi.org/10.1007/s41748-021-00199-5

16. Dahal, V., S. Gautam, and R. Bhattarai, 2018: Analysis of long-term temperature trend in Illinois and its implication on the cropping system. *Environmental Processes*, **5** (3), 451–464. https://doi.org/10.1007/s40710-018-0306-7

17. Ford, T.W., L. Chen, and J.T. Schoof, 2021: Variability and transitions in precipitation extremes in the Midwest United States. *Journal of Hydrometeorology*, **22** (3), 533–545. https://doi.org/10.1175/jhm-d-20-0216.1

18. Chen, L. and T.W. Ford, 2023: Future changes in the transitions of monthly-to-seasonal precipitation extremes over the Midwest in Coupled Model Intercomparison Project Phase 6 models. *International Journal of Climatology*, **43** (1), 255–274. https://doi.org/10.1002/joc.7756

19. Anderson, R., P.E. Bayer, and D. Edwards, 2020: Climate change and the need for agricultural adaptation. *Current Opinion in Plant Biology*, **56**, 197–202. https://doi.org/10.1016/j.pbi.2019.12.006

20. Baldwin-Kordick, R., M. De, M.D. Lopez, M. Liebman, N. Lauter, J. Marino, and M.D. McDaniel, 2022: Comprehensive impacts of diversified cropping on soil health and sustainability. *Agroecology and Sustainable Food Systems*, **46** (3), 331–363. https://doi.org/10.1080/21683565.2021.2019167

21. Walsh, M.K., P. Backlund, L. Buja, A. DeGaetano, R. Melnick, L. Prokopy, E. Takle, D. Todey, and L. Ziska, 2020: Climate Indicators for Agriculture. USDA Technical Bulletin 1953. U.S. Department of Agriculture, Washington, DC, 70 pp. https://doi.org/10.25675/10217/210930

22. Kucharik, C.J., T. Ramiadantsoa, J. Zhang, and A.R. Ives, 2020: Spatiotemporal trends in crop yields, yield variability, and yield gaps across the USA. *Crop Science*, **60** (4), 2085–2101. https://doi.org/10.1002/csc2.20089

23. Bowling, L.C., K.A. Cherkauer, C.I. Lee, J.L. Beckerman, S. Brouder, J.R. Buzan, O.C. Doering, J.S. Dukes, P.D. Ebner, J.R. Frankenberger, B.M. Gramig, E.J. Kladivko, and J.J. Volenec, 2020: Agricultural impacts of climate change in Indiana and potential adaptations. *Climatic Change*, **163** (4), 2005–2027. https://doi.org/10.1007/s10584-020-02934-9

24. English, B.C., S.A. Smith, R.J. Menard, D.W. Hughes, and M. Gunderson, 2021: Estimated economic impacts of the 2019 Midwest floods. *Economics of Disasters and Climate Change*, **5** (3), 431–448. https://doi.org/10.1007/s41885-021-00095-2

25. Hoell, A., T.W. Ford, M. Woloszyn, J.A. Otkin, and J. Eischeid, 2021: Characteristics and predictability of Midwestern United States drought. *Journal of Hydrometeorology*, **22** (11), 3087–3105. https://doi.org/10.1175/jhm-d-21-0052.1

26. Byun, K., C.M. Chiu, and A.F. Hamlet, 2019: Effects of 21st century climate change on seasonal flow regimes and hydrologic extremes over the Midwest and Great Lakes region of the US. *Science of The Total Environment*, **650**, 1261–1277. https://doi.org/10.1016/j.scitotenv.2018.09.063

27. Grady, K.A., L. Chen, and T.W. Ford, 2021: Projected changes to spring and summer precipitation in the Midwestern United States. *Frontiers in Water*, **3**, 780333. https://doi.org/10.3389/frwa.2021.780333

28. Zhou, W., L.R. Leung, and J. Lu, 2022: Seasonally dependent future changes in the U.S. Midwest hydroclimate and extremes. *Journal of Climate*, **35** (1), 17–27. https://doi.org/10.1175/jcli-d-21-0012.1

29. Hatfield, J.L., M.V.K. Sivakumar, and J.H. Prueger, Eds., 2018: *Agroclimatology: Linking Agriculture to Climate*. Vol. 60. American Society of Agronomy: Crop Science Society of America: Soil Science Society of America. https://doi.org/10.2134/agronmonogr60

30. Hatfield, J.L., L. Wright-Morton, and B. Hall, 2018: Vulnerability of grain crops and croplands in the Midwest to climatic variability and adaptation strategies. *Climatic Change*, **146** (1–2), 263–275. https://doi.org/10.1007/s10584-017-1997-x

31. Kimm, H., K. Guan, C.H. Burroughs, B. Peng, E.A. Ainsworth, C.J. Bernacchi, C.E. Moore, E. Kumagai, X. Yang, J.A. Berry, and G. Wu, 2021: Quantifying high-temperature stress on soybean canopy photosynthesis: The unique role of sun-induced chlorophyll fluorescence. *Global Change Biology*, **27** (11), 2403–2415. https://doi.org/10.1111/gcb.15603

32. Wuebbles, D., J. Angel, K. Petersen, and A.M. Lemke, 2021: An Assessment of the Impacts of Climate Change in Illinois. University of Illinois at Urbana-Champaign. https://doi.org/10.13012/b2idb-1260194_v1

33. Partridge, T.F., J.M. Winter, E.C. Osterberg, D.W. Hyndman, A.D. Kendall, and F.J. Magilligan, 2018: Spatially distinct seasonal patterns and forcings of the U.S. warming hole. *Geophysical Research Letters*, **45** (4), 2055–2063. https://doi.org/10.1002/2017gl076463

34. Alter, R.E., H.C. Douglas, J.M. Winter, and E.A.B. Eltahir, 2018: Twentieth century regional climate change during the summer in the central United States attributed to agricultural intensification. *Geophysical Research Letters*, **45** (3), 1586–1594. https://doi.org/10.1002/2017gl075604

35. Lark, T.J., S.A. Spawn, M. Bougie, and H.K. Gibbs, 2020: Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nature Communications*, **11** (1), 4295. https://doi.org/10.1038/s41467-020-18045-z

36. Mueller, N.D., E.E. Butler, K.A. McKinnon, A. Rhines, M. Tingley, N.M. Holbrook, and P. Huybers, 2016: Cooling of US Midwest summer temperature extremes from cropland intensification. *Nature Climate Change*, **6** (3), 317–322. https://doi.org/10.1038/nclimate2825

37. Nikiel, C.A. and E.A.B. Eltahir, 2019: Summer climate change in the Midwest and Great Plains due to agricultural development during the twentieth century. *Journal of Climate*, **32** (17), 5583–5599. https://doi.org/10.1175/jcli-d-19-0096.1

38. Wang, S., S. Di Tommaso, J.M. Deines, and D.B. Lobell, 2020: Mapping twenty years of corn and soybean across the US Midwest using the Landsat archive. *Scientific Data*, **7** (1), 307. https://doi.org/10.1038/s41597-020-00646-4

39. Butler, E.E., N.D. Mueller, and P. Huybers, 2018: Peculiarly pleasant weather for US maize. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (47), 11935–11940. https://doi.org/10.1073/pnas.1808035115

40. Partridge, T.F., J.M. Winter, L. Liu, A.D. Kendall, B. Basso, and D.W. Hyndman, 2019: Mid-20th century warming hole boosts US maize yields. *Environmental Research Letters*, **14**, 114008. https://doi.org/10.1088/1748-9326/ab422b

41. Rizzo, G., J.P. Monzon, F.A. Tenorio, R. Howard, K.G. Cassman, and P. Grassini, 2022: Climate and agronomy, not genetics, underpin recent maize yield gains in favorable environments. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (4), e2113629119. https://doi.org/10.1073/pnas.2113629119

42. Jägermeyr, J., C. Müller, A.C. Ruane, J. Elliott, J. Balkovic, O. Castillo, B. Faye, I. Foster, C. Folberth, J.A. Franke, K. Fuchs, J.R. Guarin, J. Heinke, G. Hoogenboom, T. Iizumi, A.K. Jain, D. Kelly, N. Khabarov, S. Lange, T.-S. Lin, W. Liu, O. Mialyk, S. Minoli, E.J. Moyer, M. Okada, M. Phillips, C. Porter, S.S. Rabin, C. Scheer, J.M. Schneider, J.F. Schyns, R. Skalsky, A. Smerald, T. Stella, H. Stephens, H. Webber, F. Zabel, and C. Rosenzweig, 2021: Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food*, **2** (11), 873–885. https://doi.org/10.1038/s43016-021-00400-y

43. Liu, L. and B. Basso, 2020: Impacts of climate variability and adaptation strategies on crop yields and soil organic carbon in the US Midwest. *PLoS One*, **15** (1), 0225433. https://doi.org/10.1371/journal.pone.0225433

44. DeLucia, E.H., S. Chen, K. Guan, B. Peng, Y. Li, N. Gomez-Casanovas, I.B. Kantola, C.J. Bernacchi, Y. Huang, S.P. Long, and D.R. Ort, 2019: Are we approaching a water ceiling to maize yields in the United States? *Ecosphere*, **10** (6), 02773. https://doi.org/10.1002/ecs2.2773

45. Rigden, A.J., N.D. Mueller, N.M. Holbrook, N. Pillai, and P. Huybers, 2020: Combined influence of soil moisture and atmospheric evaporative demand is important for accurately predicting US maize yields. *Nature Food*, **1**, 127–133. https://doi.org/10.1038/s43016-020-0028-7

46. Nocco, M.A., R.A. Smail, and C.J. Kucharik, 2019: Observation of irrigation-induced climate change in the Midwest United States. *Global Change Biology*, **25** (10), 3472–3484. https://doi.org/10.1111/gcb.14725

47. Nickles, K., A. Relling, A. García Guerra, F. Fluharty, and A. Parker, 2020: 70 cows housed in muddy environmental conditions during late gestation have lesser body weight and body condition score compared with cows housed on wood chips. *Journal of Animal Science*, **98** (Supplement_4), 48. https://doi.org/10.1093/jas/skaa278.088

48. Nickles, K., A. Relling, A. García Guerra, F. Fluharty, and A. Parker, 2021: 87 beef heifers housed in muddy environmental conditions lose body weight and body condition but meet gestational requirements for fetal growth. *Journal of Animal Science*, **99** (Supplement_3), 46. https://doi.org/10.1093/jas/skab235.081

49. Nickles, K., A.E. Relling, A. Garcia-Guerra, F.L. Fluharty, and A.J. Parker, 2021: 39 muddy environmental conditions cause conceptus free live weight loss but not a decrease in calf birth weight when compared with cows housed on wood chips. *Journal of Animal Science*, **99** (Supplement_1), 31–31. https://doi.org/10.1093/jas/skab054.054

50. Rojas-Downing, M.M., A.P. Nejadhashemi, T. Harrigan, and S.A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145–163. https://doi.org/10.1016/j.crm.2017.02.001

51. Crist, S., J. Mori, and R.L. Smith, 2020: Flooding on beef and swine farms: A scoping review of effects in the Midwestern United States. *Preventive Veterinary Medicine*, **184**, 105158. https://doi.org/10.1016/j.prevetmed.2020.105158

52. Hristov, A.N., A.T. Degaetano, C.A. Rotz, E. Hoberg, R.H. Skinner, T. Felix, H. Li, P.H. Patterson, G. Roth, M. Hall, T.L. Ott, L.H. Baumgard, W. Staniar, R.M. Hulet, C.J. Dell, A.F. Brito, and D.Y. Hollinger, 2018: Climate change effects on livestock in the Northeast US and strategies for adaptation. *Climatic Change*, **146** (1), 33–45. https://doi.org/10.1007/s10584-017-2023-z

53. Feliciano, R.J., G. Boué, and J.-M. Membré, 2020: Overview of the potential impacts of climate change on the microbial safety of the dairy industry. *Foods*, **9** (12). https://doi.org/10.3390/foods9121794

54. Gunn, K.M., M.A. Holly, T.L. Veith, A.R. Buda, R. Prasad, C.A. Rotz, K.J. Soder, and A.M.K. Stoner, 2019: Projected heat stress challenges and abatement opportunities for U.S. milk production. *PLoS ONE*, **14** (3), e0214665. https://doi.org/10.1371/journal.pone.0214665

55. Veltman, K., C.A. Rotz, L. Chase, J. Cooper, C.E. Forest, P.A. Ingraham, R.C. Izaurralde, C.D. Jones, R.E. Nicholas, M.D. Ruark, W. Salas, G. Thoma, and O. Jolliet, 2021: Assessing and reducing the environmental impact of dairy production systems in the northern US in a changing climate. *Agricultural Systems*, **192**, 103170. https://doi.org/10.1016/j.agsy.2021.103170

56. Andresen, J.A. and W.J. Baule, 2020: Ch. 16. Perennial systems (temperate fruit trees and grapes). In: *Agroclimatology: Linking Agriculture to Climate*. Hatfield, J.L., M.V. Sivakumar, and J.H. Prueger, Eds. American Society of Agronomy: Crop Science Society of America: Soil Science Society of America, 425–452. https://doi.org/10.2134/agronmonogr60.2016.0016

57. NASS, 2019: 2017 Census of Agriculture: Specialty Crops. AC-17-S-8. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/agcensus/2017/online_resources/specialty_crops/scrops.pdf

58. Kistner, E., O. Kellner, J. Andresen, D. Todey, and L.W. Morton, 2018: Vulnerability of specialty crops to short-term climatic variability and adaptation strategies in the Midwestern USA. *Climatic Change*, **146** (1), 145–158. https://doi.org/10.1007/s10584-017-2066-1

59. Khalifa, S.A.M., M.H. Elashal, N. Yosri, M. Du, S.G. Musharraf, L. Nahar, S.D. Sarker, Z. Guo, W. Cao, X. Zou, A.A. Abd El-Wahed, J. Xiao, H.A. Omar, M.-E.F. Hegazy, and H.R. El-Seedi, 2021: Bee pollen: Current status and therapeutic potential. *Nutrients*, **13** (6), 1876. https://doi.org/10.3390/nu13061876

60. Reilly, J.R., D.R. Artz, D. Biddinger, K. Bobiwash, N.K. Boyle, C. Brittain, J. Brokaw, J.W. Campbell, J. Daniels, E. Elle, J.D. Ellis, S.J. Fleischer, J. Gibbs, R.L. Gillespie, K.B. Gundersen, L. Gut, G. Hoffman, N. Joshi, O. Lundin, K. Mason, C.M. McGrady, S.S. Peterson, T.L. Pitts-Singer, S. Rao, N. Rothwell, L. Rowe, K.L. Ward, N.M. Williams, J.K. Wilson, R. Isaacs, and R. Winfree, 2020: Crop production in the USA is frequently limited by a lack of pollinators. *Proceedings of the Royal Society B: Biological Sciences*, **287** (1931), 20200922. https://doi.org/10.1098/rspb.2020.0922

61. Soroye, P., T. Newbold, and J. Kerr, 2020: Climate change contributes to widespread declines among bumble bees across continents. *Science*, **367** (6478), 685–688. https://doi.org/10.1126/science.aax8591

62. Kammerer, M., S.C. Goslee, M.R. Douglas, J.F. Tooker, and C.M. Grozinger, 2021: Wild bees as winners and losers: Relative impacts of landscape composition, quality, and climate. *Global Change Biology*, **27** (6), 1250–1265. https://doi.org/10.1111/gcb.15485

63. Bebber, D.P., M.A.T. Ramotowski, and S.J. Gurr, 2013: Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, **3** (11), 985–988. https://doi.org/10.1038/nclimate1990

64. Britt, K.E., T.P. Kuhar, W. Cranshaw, C.T. McCullough, S.V. Taylor, B.R. Arends, H. Burrack, M. Pulkoski, D. Owens, T.A. Tolosa, S. Zebelo, K.A. Kesheimer, O.S. Ajayi, M. Samuel-Foo, J.A. Davis, N. Arey, H. Doughty, J. Jones, M. Bolt, B.J. Fritz, J.F. Grant, J. Cosner, and M. Schreiner, 2021: Pest management needs and limitations for corn earworm (Lepidoptera: Noctuidae), an emergent key pest of hemp in the United States. *Journal of Integrated Pest Management*, **12** (1), 34. https://doi.org/10.1093/jipm/pmab030

65. IPCC Secretariat, 2021: Scientific Review of the Impact of Climate Change on Plant Pests–A Global Challenge to Prevent and Mitigate Plant Pest Risks in Agriculture, Forestry and Ecosystems. 978-92-5-134435-4. FAO on behalf of the IPPC Secretariat, Rome, Italy. https://doi.org/10.4060/cb4769en

66. Kistner, E.J., 2017: Climate change impacts on the potential distribution and abundance of the brown marmorated stink bug (Hemiptera: Pentatomidae) with special reference to North America and Europe. *Environmental Entomology*, **46** (6), 1212–1224. https://doi.org/10.1093/ee/nvx157

67. Kistner-Thomas, E.J., 2019: The potential global distribution and voltinism of the Japanese beetle (Coleoptera: Scarabaeidae) under current and future climates. *Journal of Insect Science*, **19** (2). https://doi.org/10.1093/jisesa/iez023

68. Taylor, R.A.J., D.A. Herms, J. Cardina, and R.H. Moore, 2018: Climate change and pest management: Unanticipated consequences of trophic dislocation. *Agronomy*, **8** (1), 7. https://doi.org/10.3390/agronomy8010007

69. Kiefer, M.T., J.A. Andresen, D.G. McCullough, W.J. Baule, and M. Notaro, 2021: Extreme minimum temperatures in the Great Lakes region of the United States: A climatology with implications for insect mortality. *International Journal of Climatology*, **42** (7), 3596–3615. https://doi.org/10.1002/joc.7434

70. Landau, C.A., A.G. Hager, and M.M. Williams II, 2021: Diminishing weed control exacerbates maize yield loss to adverse weather. *Global Change Biology*, **27** (23), 6156–6165. https://doi.org/10.1111/gcb.15857

71. Fall, M.L., J.F. Willbur, D.L. Smith, A.M. Byrne, and M.I. Chilvers, 2018: Spatiotemporal distribution pattern of *Sclerotinia sclerotiorum* apothecia is modulated by canopy closure and soil temperature in an irrigated soybean field. *Plant Disease*, **102** (9), 1794–1802. https://doi.org/10.1094/pdis-11-17-1821-re

72. Komoto, K., L. Soldo, Y. Tang, M.I. Chilvers, K. Dahlin, G. Guentchev, L. Rill, and J.A. Winkler, 2021: Climatology of persistent high relative humidity: An example for the Lower Peninsula of Michigan, USA. *International Journal of Climatology*, **41** (S1), 2517–2536. https://doi.org/10.1002/joc.6861

73. Crane-Droesch, A., E. Marshall, S. Rosch, A. Riddle, J. Cooper, and S. Wallander, 2019: Climate Change and Agricultural Risk Management into the 21st Century. ERR-266. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/webdocs/publications/93547/err-266.pdf?v=9203.7

74. Diffenbaugh, N.S., F.V. Davenport, and M. Burke, 2021: Historical warming has increased U.S. crop insurance losses. *Environmental Research Letters*, **16** (8), 084025. https://doi.org/10.1088/1748-9326/ac1223

75. Reyes, J.J. and E. Elias, 2019: Spatio-temporal variation of crop loss in the United States from 2001 to 2016. *Environmental Research Letters*, **14** (7), 074017. https://doi.org/10.1088/1748-9326/ab1ac9

76. Maxwell, J.T., G.L. Harley, and S.M. Robeson, 2016: On the declining relationship between tree growth and climate in the Midwest United States: The fading drought signal. *Climatic Change*, **138** (1), 127–142. https://doi.org/10.1007/s10584-016-1720-3

77. Thaler, E.A., I.J. Larsen, and Q. Yu, 2021: The extent of soil loss across the US Corn Belt. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (8), e1922375118. https://doi.org/10.1073/pnas.1922375118

78. Basara, J.B., J.I. Christian, R.A. Wakefield, J.A. Otkin, E.H. Hunt, and D.P. Brown, 2019: The evolution, propagation, and spread of flash drought in the Central United States during 2012. *Environmental Research Letters*, **14** (8), 084025. https://doi.org/10.1088/1748-9326/ab2cc0

79. Otkin, J.A., M. Svoboda, E.D. Hunt, T.W. Ford, M.C. Anderson, C. Hain, and J.B. Basara, 2018: Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bulletin of the American Meteorological Society*, **99** (5), 911–919. https://doi.org/10.1175/bams-d-17-0149.1

80. FAO, 2023: Economic and Policy Analysis of Climate Change: EX-ACT and Climate-Smart Agriculture (CSA). Food and Agriculture Organization of the United Nations, accessed September 22, 2023. https://www.fao.org/in-action/epic/ex-act-tool/overview/ex-act-and-csa/en/

81. Chandra, A., K.E. McNamara, and P. Dargusch, 2018: Climate-smart agriculture: Perspectives and framings. *Climate Policy*, **18** (4), 526–541. https://doi.org/10.1080/14693062.2017.1316968

82. Deines, J.M., K. Guan, B. Lopez, Q. Zhou, C.S. White, S. Wang, and D.B. Lobell, 2023: Recent cover crop adoption is associated with small maize and soybean yield losses in the United States. *Global Change Biology*, **29** (3), 794–807. https://doi.org/10.1111/gcb.16489

83. Qin, Z., K. Guan, W. Zhou, B. Peng, M.B. Villamil, Z. Jin, J. Tang, R. Grant, L. Gentry, A.J. Margenot, G. Bollero, and Z. Li, 2021: Assessing the impacts of cover crops on maize and soybean yield in the U.S. Midwestern agroecosystems. *Field Crops Research*, **273**, 108264. https://doi.org/10.1016/j.fcr.2021.108264

84. Basso, B., G. Shuai, J. Zhang, and G.P. Robertson, 2019: Yield stability analysis reveals sources of large-scale nitrogen loss from the US Midwest. *Scientific Reports*, **9** (1), 5774. https://doi.org/10.1038/s41598-019-42271-1

85. Maestrini, B. and B. Basso, 2021: Subfield crop yields and temporal stability in thousands of US Midwest fields. *Precision Agriculture*, **22** (6), 1749–1767. https://doi.org/10.1007/s11119-021-09810-1

86. Basso, B., R.A. Martinez-Feria, L. Rill, and J.T. Ritchie, 2021: Contrasting long-term temperature trends reveal minor changes in projected potential evapotranspiration in the US Midwest. *Nature Communications*, **12** (1), 1476. https://doi.org/10.1038/s41467-021-21763-7

87. Baule, W.J. 2022: Climatic Variability and Change in the Midwestern United States: Implications for Nitrogen Leaching in Agricultural Systems. Doctor of Philosophy in Geography, Michigan State University. https://lter.kbs.msu.edu/pub/4046

88. Khanna, M., D. Rajagopal, and D. Zilberman, 2021: Lessons learned from US experience with biofuels: Comparing the hype with the evidence. *Review of Environmental Economics and Policy*, **15** (1), 67–86. https://doi.org/10.1086/713026

89. Chen, H., J.M. Samet, P.A. Bromberg, and H. Tong, 2021: Cardiovascular health impacts of wildfire smoke exposure. *Particle and Fibre Toxicology*, **18** (1), 2. https://doi.org/10.1186/s12989-020-00394-8

90. Field, J.L., T.L. Richard, E.A.H. Smithwick, H. Cai, M.S. Laser, D.S. LeBauer, S.P. Long, K. Paustian, Z. Qin, J.J. Sheehan, P. Smith, M.Q. Wang, and L.R. Lynd, 2020: Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (36), 21968–21977. https://doi.org/10.1073/pnas.1920877117

91. Moore, K.J., C.L. Kling, and D.R. Raman, 2020: A Midwest USA perspective on von Cossel et al.'s prospects of bioenergy cropping systems for a more social-ecologically sound bioeconomy. *Agronomy*, **10** (11). https://doi.org/10.3390/agronomy10111658

92. Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman, and D.P.M. Zaks, 2011: Solutions for a cultivated planet. *Nature*, **478** (7369), 337–342. https://doi.org/10.1038/nature10452

93. Reo, N.J. and L.A. Ogden, 2018: Anishnaabe Aki: An indigenous perspective on the global threat of invasive species. *Sustainability Science*, **13**, 1443–1452. https://doi.org/10.1007/s11625-018-0571-4

94. DOI, FWS, DOC, and USCB, 2016: National Survey of Fishing, Hunting, and Wildlife-Associated Recreation. U.S. Department of the Interior, U.S. Fish and Wildlife Service, U.S. Department of Commerce, and U.S. Census Bureau. https://www.census.gov/content/dam/Census/library/publications/2018/demo/fhw16-nat.pdf

95. White, M.P., I. Alcock, J. Grellier, B.W. Wheeler, T. Hartig, S.L. Warber, A. Bone, M.H. Depledge, and L.E. Fleming, 2019: Spending at least 120 minutes a week in nature is associated with good health and wellbeing. *Scientific Reports*, **9** (1), 7730. https://doi.org/10.1038/s41598-019-44097-3

96. Mitchell, R. and F. Popham, 2008: Effect of exposure to natural environment on health inequalities: An observational population study. *The Lancet*, **372** (9650), 1655–1660. https://doi.org/10.1016/s0140-6736(08)61689-x

97. Paukert, C., J.D. Olden, A.J. Lynch, D.D. Breshears, R.C. Chambers, C. Chu, M. Daly, K.L. Dibble, J. Falke, D. Issak, P. Jacobson, O.P. Jensen, and D. Munroe, 2021: Climate change effects on North American fish and fisheries to inform adaptation strategies. *Fisheries*, **46** (9), 449–464. https://doi.org/10.1002/fsh.10668

98. Hansen, G.J.A., T.D. Ahrenstorff, B.J. Bethke, J.D. Dumke, J. Hirsch, K.E. Kovalenko, J.F. LeDuc, R.P. Maki, H.M. Rantala, and T. Wagner, 2020: Walleye growth declines following zebra mussel and *Bythotrephes* invasion. *Biological Invasions*, **22**, 1481–1495. https://doi.org/10.1007/s10530-020-02198-5

99. Höök, T.O., C.J. Foley, P. Collingsworth, L. Dorworth, B. Fisher, J.T. Hoverman, E. LaRue, M. Pyron, and J. Tank, 2020: An assessment of the potential impacts of climate change on freshwater habitats and biota of Indiana, USA. *Climatic Change*, **163** (4), 1897–1916. https://doi.org/10.1007/s10584-019-02502-w

100. Jacobson, P.C., G.J.A. Hansen, B.J. Bethke, and T.K. Cross, 2017: Disentangling the effects of a century of eutrophication and climate warming on freshwater lake fish assemblages. *PLoS One*, **12** (8), 0182667. https://doi.org/10.1371/journal.pone.0182667

101. Murdoch, A., C. Mantyka-Pringle, and S. Sharma, 2020: The interactive effects of climate change and land use on boreal stream fish communities. *Science of The Total Environment*, **700**, 134518. https://doi.org/10.1016/j.scitotenv.2019.134518

102. Hansen, G.J.A., J.S. Read, J.F. Hansen, and L.A. Winslow, 2017: Projected shifts in fish species dominance in Wisconsin lakes under climate change. *Global Change Biology*, **23** (4), 1463–1476. https://doi.org/10.1111/gcb.13462

103. Hansen, G.J.A., J. Ruzich, C.A. Krabbenhoft, H. Kundel, S. Mahlum, C.I. Rounds, A.O. Van Pelt, L.D. Eslinger, D.E. Logsdon, and D.A. Isermann, 2022: It's complicated and it depends: A review of the effects of ecosystem changes on walleye and yellow perch populations in North America. *North American Journal of Fisheries Management*, **42** (3), 484–506. https://doi.org/10.1002/nafm.10741

104. Hansen, G.J.A., L.A. Winslow, J.S. Read, M. Treml, P.J. Schmalz, and S.R. Carpenter, 2019: Water clarity and temperature effects on walleye safe harvest: An empirical test of the safe operating space concept. *Ecosphere*, **10** (5), 02737. https://doi.org/10.1002/ecs2.2737

105. Till, A., A.L. Rypel, A. Bray, and S.B. Fey, 2019: Fish die-offs are concurrent with thermal extremes in north temperate lakes. *Nature Climate Change*, **9**, 637–641. https://doi.org/10.1038/s41558-019-0520-y

106. Death, R.G., I.C. Fuller, and M.G. Macklin, 2015: Resetting the river template: The potential for climate-related extreme floods to transform river geomorphology and ecology. *Freshwater Biology*, **60** (12), 2477–2496. https://doi.org/10.1111/fwb.12639

107. Choi, C., P. Berry, and A. Smith, 2021: The climate benefits, co-benefits, and trade-offs of green infrastructure: A systematic literature review. *Journal of Environmental Management*, **291**, 112583. https://doi.org/10.1016/j.jenvman.2021.112583

108. Demaria, E.M.C., R.N. Palmer, and J.K. Roundy, 2016: Regional climate change projections of streamflow characteristics in the Northeast and Midwest U.S. *Journal of Hydrology: Regional Studies*, **5**, 309–323. https://doi.org/10.1016/j.ejrh.2015.11.007

109. Tsang, Y., D.M. Infante, L. Wang, D. Krueger, and D. Wieferich, 2021: Conserving stream fishes with changing climate: Assessing fish responses to changes in habitat over a large region. *Science of The Total Environment*, **755** (2), 142503. https://doi.org/10.1016/j.scitotenv.2020.142503

110. Mitro, M.G., J.D. Lyons, J.S. Stewart, P.K. Cunningham, and J.D.T. Griffin, 2019: Projected changes in brook trout and brown trout distribution in Wisconsin streams in the mid-twenty-first century in response to climate change. *Hydrobiologia*, **840** (1), 215–226. https://doi.org/10.1007/s10750-019-04020-3

111. Usinowicz, J., J. Qiu, and A. Kamarainen, 2017: Flashiness and flooding of two lakes in the Upper Midwest during a century of urbanization and climate change. *Ecosystems*, **20**, 601–615. https://doi.org/10.1007/s10021-016-0042-7

112. Palmer, R.N., K.H. Nislow, P. McIntyre, M. Ocana, K. Kahl, K. Lutz, B. Backiel, A. Ericson, E. Lotter, S. Pfiefle, and M. Saleeba, 2020: Slowing the Flow for Climate Resilience: Reducing Vulnerability to Extreme Flood and Drought Events. University of Massachusetts, Northeast Climate Adaptation Science Center, Amherst, MA. https://necasc.umass.edu/sites/default/files/styles/desktop_x1_1400px_/public/2020-00/Slow-the-Flow-_schematic2.jpg?itok=BoxKBGx6

113. Zhang, X., T.J. Lark, C.M. Clark, Y. Yuan, and S.D. LeDuc, 2021: Grassland-to-cropland conversion increased soil, nutrient, and carbon losses in the US Midwest between 2008 and 2016. *Environmental Research Letters*, **16**, 054018. https://doi.org/10.1088/1748-9326/abecbe

114. Jarzyna, M.A., B. Zuckerberg, A.O. Finley, and W.F. Porter, 2016: Synergistic effects of climate and land cover: Grassland birds are more vulnerable to climate change. *Landscape Ecology*, **31**, 2275–2290. https://doi.org/10.1007/s10980-016-0399-1

115. Zuckerberg, B., C.A. Ribic, and L.A. McCauley, 2018: Effects of temperature and precipitation on grassland bird nesting success as mediated by patch size. *Conservation Biology*, **32** (4), 872–882. https://doi.org/10.1111/cobi.13089

116. Patterson, T.A., R. Grundel, J.D.K. Dzurisin, R.L. Knutson, and J.J. Hellmann, 2020: Evidence of an extreme weather-induced phenological mismatch and a local extirpation of the endangered Karner blue butterfly. *Conservation Science and Practice*, **2** (1), 147. https://doi.org/10.1111/csp2.147

117. Zylstra, E.R., L. Ries, N. Neupane, S.P. Saunders, M.I. Ramírez, E. Rendón-Salinas, K.S. Oberhauser, M.T. Farr, and E.F. Zipkin, 2021: Changes in climate drive recent monarch butterfly dynamics. *Nature Ecology & Evolution*, **5**, 1441–1452. https://doi.org/10.1038/s41559-021-01504-1

118. Alstad, A.O., E.I. Damschen, T.J. Givnish, J.A. Harrington, M.K. Leach, D.A. Rogers, and D.M. Waller, 2016: The pace of plant community change is accelerating in remnant prairies. *Science Advances*, **2** (2), e1500975. https://doi.org/10.1126/sciadv.1500975

119. Henn, J.J. and E.I. Damschen, 2022: Grassland management actions influence soil conditions and plant community responses to winter climate change. *Ecosphere*, **13** (10), e4270. https://doi.org/10.1002/ecs2.4270

120. Ratcliffe, H., M. Ahlering, D. Carlson, S. Vacek, A. Allstadt, and L.E. Dee, 2022: Invasive species do not exploit early growing seasons in burned tallgrass prairies. *Ecological Applications*, **32** (7), e2641. https://doi.org/10.1002/eap.2641

121. Frelich, L., C.G. Lorimer, and M.C. Stambaugh, 2021: Ch. 7. History and future of fire in hardwood and conifer forests of the Great Lakes-Northeastern Forest Region, USA. In: *Fire Ecology and Management: Past, Present, and Future of US Forested Ecosystems. Managing Forest Ecosystems*. Greenberg, C.H. and B. Collins, Eds. Springer, Cham, Switzerland, 243–285. https://doi.org/10.1007/978-3-030-73267-7_7

122. Gao, P., A.J. Terando, J.A. Kupfer, J. Morgan Varner, M.C. Stambaugh, T.L. Lei, and J. Kevin Hiers, 2021: Robust projections of future fire probability for the conterminous United States. *Science of The Total Environment*, **789**, 147872. https://doi.org/10.1016/j.scitotenv.2021.147872

123. Stambaugh, M.C., B.O. Knapp, and D.C. Dey, 2021: Ch. 5. Fire ecology and management of forest ecosystems in the Western Central Hardwoods and Prairie-Forest Border. In: *Fire Ecology and Management: Past, Present, and Future of US Forested Ecosystems*. Greenberg, C.H. and B. Collins, Eds. Springer, Cham, Switzerland, 149–199. https://doi.org/10.1007/978-3-030-73267-7_5

124. Otkin, J.A., M. Woloszyn, H. Wang, M. Svoboda, M. Skumanich, R. Pulwarty, J. Lisonbee, A. Hoell, M. Hobbins, T. Haigh, and A.E. Cravens, 2022: Getting ahead of flash drought: From early warning to early action. *Bulletin of the American Meteorological Society*, **103** (10), E2188–E2202. https://doi.org/10.1175/bams-d-21-0288.1

125. Pendergrass, A.G., G.A. Meehl, R. Pulwarty, M. Hobbins, A. Hoell, A. AghaKouchak, C.J.W. Bonfils, A.J.E. Gallant, M. Hoerling, D. Hoffmann, L. Kaatz, F. Lehner, D. Llewellyn, P. Mote, R.B. Neale, J.T. Overpeck, A. Sheffield, K. Stahl, M. Svoboda, M.C. Wheeler, A.W. Wood, and C.A. Woodhouse, 2020: Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nature Climate Change*, **10**, 191–199. https://doi.org/10.1038/s41558-020-0709-0

126. Christian, J.I., J.B. Basara, E.D. Hunt, J.A. Otkin, J.C. Furtado, V. Mishra, X. Xiao, and R.M. Randall, 2021: Global distribution, trends, and drivers of flash drought occurrence. *Nature Communications*, **12**, 6330. https://doi.org/10.1038/s41467-021-26692-z

127. Wood, J.D., B.O. Knapp, R.M. Muzika, M.C. Stambaugh, and L. Gu, 2018: The importance of drought–pathogen interactions in driving oak mortality events in the Ozark border region. *Environmental Research Letters*, **13** (1), 015004. https://doi.org/10.1088/1748-9326/aa94fa

128. De Jager, N.R., M. Van Appledorn, T.J. Fox, J.J. Rohweder, L.J. Guyon, A.R. Meier, R.J. Cosgriff, and B.J. Vandermyde, 2019: Spatially explicit modelling of floodplain forest succession: Interactions among flood inundation, forest successional processes, and other disturbances in the Upper Mississippi River floodplain, USA. *Ecological Modelling*, **405**, 15–32. https://doi.org/10.1016/j.ecolmodel.2019.05.002

129. King, D.J., G.L. Harley, J.T. Maxwell, K.J. Heeter, B.J. Vandermyde, and R.J. Cosgriff, 2021: Floodplain forest structure and the recent decline of *Carya illinoinensis* (Wangenh.) K. Koch (Northern pecan) at its northern latitudinal range margin, Upper Mississippi River System, USA. *Forest Ecology and Management*, **496**, 119454. https://doi.org/10.1016/j.foreco.2021.119454

130. Klooster, W.S., K.J.K. Gandhi, L.C. Long, K.I. Perry, K.B. Rice, and D.A. Herms, 2018: Ecological impacts of emerald ash borer in forests at the epicenter of the invasion in North America. *Forests*, **9** (5), 250. https://doi.org/10.3390/f9050250

131. Phillips, R.P., L. Brandt, P.D. Polly, P. Zollner, M.R. Saunders, K. Clay, L. Iverson, and S. Fei, 2020: An integrated assessment of the potential impacts of climate change on Indiana forests. *Climatic Change*, **163**, 1917–1931. https://doi.org/10.1007/s10584-018-2326-8

132. Tribal Adaptation Menu Team, 2019: Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu. Great Lakes Indian Fish and Wildlife Commission, Odanah, WI, 54 pp. https://forestadaptation.org/tribal-climate-adaptation-menu

133. Contosta, A.R., N.J. Casson, S. Garlick, S.J. Nelson, M.P. Ayres, E.A. Burakowski, J. Campbell, I. Creed, C. Eimers, C. Evans, I. Fernandez, C. Fuss, T. Huntington, K. Patel, R. Sanders-DeMott, K. Son, P. Templer, and C. Thornbrugh, 2019: Northern forest winters have lost cold, snowy conditions that are important for ecosystems and human communities. *Ecological Applications*, **29** (7), 01974. https://doi.org/10.1002/eap.1974

134. Contosta, A.R., N.J. Casson, S.J. Nelson, and S. Garlick, 2020: Defining frigid winter illuminates its loss across seasonally snow-covered areas of eastern North America. *Environmental Research Letters*, **15** (3), 034020. https://doi.org/10.1088/1748-9326/ab54f3

135. Zuckerberg, B. and J.N. Pauli, 2018: Conserving and managing the subnivium. *Conservation Biology*, **32** (4), 774–781. https://doi.org/10.1111/cobi.13091

136. Marks-Marino, D., 2019: 1854 Treaty Authority. Northern Arizona University, Institute for Tribal Environmental Professionals. http://www7.nau.edu/itep/main/tcc/Tribes/gl_trAuth

137. Moore, S., 2012: Grand Portage Band of Lake Superior Chippewa: Creative Solutions for a Changing Environment. Northern Arizona University, Institute for Tribal Environmental Professionals, Climate Change Program. http://www7.nau.edu/itep/main/tcc/Tribes/gl_gpchippewa

138. Teitelbaum, C.S., A.P.K. Sirén, E. Coffel, J.R. Foster, J.L. Frair, J.W. Hinton, R.M. Horton, D.W. Kramer, C. Lesk, C. Raymond, D.W. Wattles, K.A. Zeller, and T.L. Morelli, 2021: Habitat use as indicator of adaptive capacity to climate change. *Diversity and Distributions*, **27** (4), 655–667. https://doi.org/10.1111/ddi.13223

139. Weiskopf, S.R., O.E. Ledee, and L.M. Thompson, 2019: Climate change effects on deer and moose in the Midwest. *The Journal of Wildlife Management*, **83** (4), 769–781. https://doi.org/10.1002/jwmg.21649

140. Billiot, S., S. Kwon, and C.E. Burnette, 2019: Repeated disasters and chronic environmental changes impede generational transmission of Indigenous knowledge. *Journal of Family Strengths*, **19** (1), 11. https://digitalcommons.library.tmc.edu/jfs/vol19/iss1/11

141. Bond, M.O., B.J. Anderson, T.H.A. Henare, and P.M. Wehi, 2019: Effects of climatically shifting species distributions on biocultural relationships. *People and Nature*, **1** (1), 87–102. https://doi.org/10.1002/pan3.15

142. Daigle, J.J., N. Michelle, D.J. Ranco, and M.R. Emery, 2019: Traditional lifeways and storytelling: Tools for adaptation and resilience to ecosystem change. *Human Ecology*, **47** (5), 777–784. https://doi.org/10.1007/s10745-019-00113-8

143. Pearson, J., G. Jackson, and K.E. McNamara, 2023: Climate-driven losses to Indigenous and local knowledge and cultural heritage. *The Anthropocene Review*, **10** (2), 343–366. https://doi.org/10.1177/20530196211005482

144. Panci, H., M. Montano, A. Shultz, T. Bartnick, and K. Stone, 2018: Climate Change Vulnerability Assessment: Integrating Scientific and Traditional Ecological Knowledge. Version 1. Coleman, J., E. Chiriboga, A.M. Soltis, and J. Gilbert, Eds. Great Lakes Indian Fish and Wildlife Commission. https://glifwc.org/ClimateChange/GLIFWC_Climate_Change_Vulnerability_Assessment_Version1_April2018.pdf

145. Dooper, S., K. Proudman, A. Osielski, S. Swanz, and A. Zaman, 2018: Assessing Potential Non-Economic Loss & Damage from Climate Change: Partnership with the Bad River Band of the Lake Superior Chippewa Indians. University of Michigan, Ann Arbor, MI. https://hdl.handle.net/2027.42/150173

146. Marks-Marino, D., 2019: The Bad River Band of Lake Superior Chippewa (Ojibwe). Northern Arizona University, Institute for Tribal Environmental Professionals, Climate Change Program. http://www7.nau.edu/itep/main/tcc/tribes/gl_badriver

147. Stoffle, R.W., M.J. Evans, C.S. Sittler, D.L. Berry, and K. Van Vlack, 2022: Climate change and Odawa cultural plants in Sleeping Bear Dunes National Lake Shore. *Climatic Change*. https://doi.org/10.21203/rs.3.rs-869301/v1

148. Hatfield, S.C., E. Marino, K.P. Whyte, K.D. Dello, and P.W. Mote, 2018: Indian time: Time, seasonality, and culture in Traditional Ecological Knowledge of climate change. *Ecological Processes*, **7**, 25. https://doi.org/10.1186/s13717-018-0136-6

149. Embke, H.S., T.D. Beard Jr., A.J. Lynch, and M.J.V. Zanden, 2020: Fishing for food: Quantifying recreational fisheries harvest in Wisconsin lakes. *Fisheries*, **45** (12), 647–655. https://doi.org/10.1002/fsh.10486

150. Filazzola, A., K. Blagrave, M.A. Imrit, and S. Sharma, 2020: Climate change drives increases in extreme events for lake ice in the Northern Hemisphere. *Geophysical Research Letters*, **47** (18), 2020GL089608. https://doi.org/10.1029/2020gl089608

151. Knoll, L.B., S. Sharma, B.A. Denfeld, G. Flaim, Y. Hori, J.J. Magnuson, D. Straile, and G.A. Weyhenmeyer, 2019: Consequences of lake and river ice loss on cultural ecosystem services. *Limnology and Oceanography Letters*, **4** (5), 119–131. https://doi.org/10.1002/lol2.10116

152. Sharma, S., K. Blagrave, S.R. Watson, C.M. O'Reilly, R. Batt, J.J. Magnuson, T. Clemens, B.A. Denfeld, G. Flaim, L. Grinberga, Y. Hori, A. Laas, L.B. Knoll, D. Straile, N. Takamura, and G.A. Weyhenmeyer, 2020: Increased winter drownings in ice-covered regions with warmer winters. *PLoS ONE*, **15** (11), e0241222. https://doi.org/10.1371/journal.pone.0241222

153. Ontl, T.A., C. Swanston, L.A. Brandt, P.R. Butler, A.W. D'Amato, S.D. Handler, M.K. Janowiak, and P.D. Shannon, 2018: Adaptation pathways: Ecoregion and land ownership influences on climate adaptation decision-making in forest management. *Climatic Change*, **146** (1), 75–88. https://doi.org/10.1007/s10584-017-1983-3

154. White, M.A., M.W. Cornett, K. Frerker, and J.R. Etterson, 2020: Partnerships to take on climate change: Adaptation forestry and conifer strongholds projects in the Northwoods, Minnesota, USA. *Journal of Forestry*, **118** (3), 219–232. https://doi.org/10.1093/jofore/fvaa005

155. Muller, J.J., L.M. Nagel, and B.J. Palik, 2021: Comparing long-term projected outcomes of adaptive silvicultural approaches aimed at climate change in red pine forests of northern Minnesota, USA. *Canadian Journal of Forest Research*, **51** (12), 1875–1887. https://doi.org/10.1139/cjfr-2021-0097

156. Tingley, R.W., C. Paukert, G.G. Sass, P.C. Jacobson, G.J.A. Hansen, A.J. Lynch, and P.D. Shannon, 2019: Adapting to climate change: Guidance for the management of inland glacial lake fisheries. *Lake and Reservoir Management*, **35** (4), 435–452. https://doi.org/10.1080/10402381.2019.1678535

157. Magee, M.R., C.L. Hein, J.R. Walsh, P.D. Shannon, M.J. Vander Zanden, T.B. Campbell, G.J.A. Hansen, J. Hauxwell, G.D. LaLiberte, T.P. Parks, G.G. Sass, C.W. Swanston, and M.K. Janowiak, 2019: Scientific advances and adaptation strategies for Wisconsin lakes facing climate change. *Lake and Reservoir Management*, **35** (4), 364–381. https://doi.org/10.1080/10402381.2019.1622612

158. IPBES, 2019: *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Díaz, S., J. Settele, E.S. Brondízio, H.T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K.A. Brauman, S.H.M. Butchart, K.M.A. Chan, L.A. Garibaldi, K. Ichii, J. Liu, S.M. Subramanian, G.F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y.J. Shin, I.J. Visseren-Hamakers, K.J. Willis, and C.N. Zayas, Eds. IPBES Secretariat, Bonn, Germany, 56 pp. https://www.ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf

159. Seddon, N., A. Chausson, P. Berry, C.A.J. Girardin, A. Smith, and B. Turner, 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

160. NCEI, 2022: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

161. Davenport, F.V., M. Burke, and N.S. Diffenbaugh, 2021: Contribution of historical precipitation change to US flood damages. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (4), e2017524118. https://doi.org/10.1073/pnas.2017524118

162. Johnson, K.A., O.E.J. Wing, P.D. Bates, J. Fargione, T. Kroeger, W.D. Larson, C.C. Sampson, and A.M. Smith, 2020: A benefit–cost analysis of floodplain land acquisition for US flood damage reduction. *Nature Sustainability*, **3** (1), 56–62. https://doi.org/10.1038/s41893-019-0437-5

163. Cheng, F.Y., K.J. Van Meter, D.K. Byrnes, and N.B. Basu, 2020: Maximizing US nitrate removal through wetland protection and restoration. *Nature*, **588** (7839), 625–630. https://doi.org/10.1038/s41586-020-03042-5

164. Johnson, T., J. Butcher, S. Santell, S. Schwartz, S. Julius, and S. LeDuc, 2022: A review of climate change effects on practices for mitigating water quality impacts. *Journal of Water and Climate Change*, **13** (4), 1684–1705. https://doi.org/10.2166/wcc.2022.363

165. Anderegg, W.R.L., A.T. Trugman, G. Badgley, C.M. Anderson, A. Bartuska, P. Ciais, D. Cullenward, C.B. Field, J. Freeman, S.J. Goetz, J.A. Hicke, D. Huntzinger, R.B. Jackson, J. Nickerson, S. Pacala, and J.T. Randerson, 2020: Climate-driven risks to the climate mitigation potential of forests. *Science*, **368** (6497), 7005. https://doi.org/10.1126/science.aaz7005

166. Bossio, D.A., S.C. Cook-Patton, P.W. Ellis, J. Fargione, J. Sanderman, P. Smith, S. Wood, R.J. Zomer, M. Unger, I.M. Emmer, and B.W. Griscom, 2020: The role of soil carbon in natural climate solutions. *Nature Sustainability*, **3**, 391–398. https://doi.org/10.1038/s41893-020-0491-z

167. Fargione, J.E., S. Bassett, T. Boucher, S.D. Bridgham, R.T. Conant, S.C. Cook-patton, P.W. Ellis, A. Falcucci, J.W. Fourqurean, T. Gopalakrishna, H. Gu, B. Henderson, M.D. Hurteau, K.D. Kroeger, T. Kroeger, T.J. Lark, S.M. Leavitt, G. Lomax, R.I. McDonald, J.P. Megonigal, D.A. Miteva, C.J. Richardson, J. Sanderman, D. Shoch, S.A. Spawn, J.W. Veldman, C.A. WIlliams, P.B. Woodbury, C. Zganjar, M. Baranski, R.A. Houghton, E. Landis, E. McGlynn, W.H. Schlesinger, J.V. Siikamakiariana, E. Sutton-Grierand, and B.W. Griscom, 2018: Natural climate solutions for the United States. *Science Advances*, **4** (11), 1869. https://doi.org/10.1126/sciadv.aat1869

168. Griscom, B.W., J. Adams, P.W. Ellis, R.A. Houghton, G. Lomax, D.A. Miteva, W.H. Schlesinger, D. Shoch, J.V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R.T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M.R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S.M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F.E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, and J. Fargione, 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

169. Michigan DNR, 2023: DNR State Forecast Carbon Projects. Michigan Department of Natural Resources, accessed April 27, 2023. https://www.michigan.gov/dnr/buy-and-apply/carbon

170. Reich, P.B., S.E. Hobbie, T.D. Lee, R. Rich, M.A. Pastore, and K. Worm, 2020: Synergistic effects of four climate change drivers on terrestrial carbon cycling. *Nature Geoscience*, **13**, 787–793. https://doi.org/10.1038/s41561-020-00657-1

171. Krause, L., K.J. McCullough, E.S. Kane, R.K. Kolka, R.A. Chimner, and E.A. Lilleskov, 2021: Impacts of historical ditching on peat volume and carbon in northern Minnesota USA peatlands. *Journal of Environmental Management*, **296**, 113090. https://doi.org/10.1016/j.jenvman.2021.113090

172. Prince, H., 1997: *Wetlands of the American Midwest: A Historical Geography of Changing Attitudes*. University of Chicago Press, 410 pp. https://press.uchicago.edu/ucp/books/book/chicago/W/bo3633450.html

173. Naidu, D.G.T. and S. Bagchi, 2021: Greening of the earth does not compensate for rising soil heterotrophic respiration under climate change. *Global Change Biology*, **27** (10), 2029–2038. https://doi.org/10.1111/gcb.15531

174. Hanson, P.J., N.A. Griffiths, C.M. Iversen, R.J. Norby, S.D. Sebestyen, J.R. Phillips, J.P. Chanton, R.K. Kolka, A. Malhotra, K.C. Oleheiser, J.M. Warren, X. Shi, X. Yang, J. Mao, and D.M. Ricciuto, 2020: Rapid net carbon loss from a whole-ecosystem warmed peatland. *AGU Advances*, **1** (3), e2020AV000163. https://doi.org/10.1029/2020av000163

175. Stults, M., S. Petersen, J. Bell, W. Baule, E. Nasser, E. Gibbons, and M. Fougerat, 2016: Climate Change Vulnerability Assessment and Adaptation Plan: 1854 Ceded Territory Including the Bois Forte, Fond du Lac, and Grand Portage Reservations. 1854 Ceded Territory, Duluth, MN, 146 pp. https://www.1854treatyauthority.org/images/ClimateAdaptationPlan_Final-July_2016-optimized(1).pdf

176. CTKW, 2014: Guidelines for Considering Traditional Knowledges (TKs) in Climate Change Initiatives. Climate and Traditional Knowledges Workgroup. https://climatetkw.wordpress.com

177. Koski, J., J. Vanator, M. Montano, J. Ballinger, V. Gagnon, J. Lackey, E. Ravindran, and J.L. Jock, 2021: Guidance Document on Traditional Ecological Knowledge Pursuant to the Great Lakes Water Quality Agreement. U.S. Caucus of the Traditional Ecological Knowledge, 34 pp. https://www.bia.gov/sites/default/files/dup/assets/bia/wstreg/Guidance_Document_on_TEK_Pursuant_to_the_Great_Lakes_Water_Quality_Agreement.pdf

178. Chin, N., K. Byun, A.F. Hamlet, and K.A. Cherkauer, 2018: Assessing potential winter weather response to climate change and implications for tourism in the U.S. Great Lakes and Midwest. *Journal of Hydrology: Regional Studies*, **19**, 42–56. https://doi.org/10.1016/j.ejrh.2018.06.005

179. Sampson, N.R., C.E. Price, J. Kassem, J. Doan, and J. Hussein, 2019: "We're just sitting ducks": Recurrent household flooding as an underreported environmental health threat in Detroit's changing climate. *International Journal of Environmental Research and Public Health*, **16** (1), 6. https://doi.org/10.3390/ijerph16010006

180. Bernstein, A.S., S. Sun, K.R. Weinberger, K.R. Spangler, P.E. Sheffield, and G.A. Wellenius, 2022: Warm season and emergency department visits to U.S. children's hospitals. *Environmental Health Perspectives*, **130** (1), 017001. https://doi.org/10.1289/ehp8083

181. Liu, J., L.P. Clark, M.J. Bechle, A. Hajat, S.Y. Kim, A.L. Robinson, L. Sheppard, A.A. Szpiro, and J.D. Marshall, 2021: Disparities in air pollution exposure in the United States by race/ethnicity and income, 1990–2010. *Environmental Health Perspectives*, **129** (12), 127005. https://doi.org/10.1289/ehp8584

182. National Academies of Sciences, Engineering, and Medicine, 2022: *Communities, Climate Change, and Health Equity: Proceedings of a Workshop–In Brief*. The National Academies Press, Washington, DC, 12 pp. https://doi.org/10.17226/26435

183. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. https://doi.org/10.3390/cli8010012

184. Muñoz, C.E. and E. Tate, 2016: Unequal recovery? Federal resource distribution after a Midwest flood disaster. *International Journal of Environmental Research and Public Health*, **13** (5), 507. https://doi.org/10.3390/ijerph13050507

185. Hsiao, V., T. Chandereng, R.L. Lankton, J.A. Huebner, J.J. Baltus, G.E. Flood, S.M. Dean, A.J. Tevaarwek, and D.F. Schneider, 2021: Disparities in telemedicine access: A cross-sectional study of a newly established infrastructure during the COVID-19 pandemic. *Applied Clinical Informatics*, **12** (3), 445–458. https://doi.org/10.1055/s-0041-1730026

186. ALA, 2022: State of the Air 2022. American Lung Association. https://www.lung.org/getmedia/74b3d3d3-88d1-4335-95d8-c4e47d0282c1/sota-2022.pdf

187. Dedoussi, I.C., S.D. Eastham, E. Monier, and S.R.H. Barrett, 2020: Premature mortality related to United States cross-state air pollution. *Nature*, **578**, 261–265. https://doi.org/10.1038/s41586-020-1983-8

188. Fann, N.L., C.G. Nolte, M.C. Sarofim, J. Martinich, and N.J. Nassikas, 2021: Associations between simulated future changes in climate, air quality, and human health. *JAMA Network Open*, **4** (1), e2032064. https://doi.org/10.1001/jamanetworkopen.2020.32064

189. Nassikas, N., K. Spangler, N. Fann, C.G. Nolte, P. Dolwick, T.L. Spero, P. Sheffield, and G.A. Wellenius, 2021: Ozone-related asthma emergency department visits in the US in a warming climate. *Environmental Research*, **183**, 109206. https://doi.org/10.1016/j.envres.2020.109206

190. Limaye, V.S., W. Max, J. Constible, and K. Knowlton, 2019: Estimating the health-related costs of 10 climate-sensitive U.S. events during 2012. *GeoHealth*, **3** (9), 245–265. https://doi.org/10.1029/2019gh000202

191. EPA, 2017: Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. EPA 430-R-17-001. U.S. Environmental Protection Agency, Washington, DC. https://www.epa.gov/cira/multi-model-framework-quantitative-sectoral-impacts-analysis

192. Scott, J.H., A.M. Brough, J.W. Gilbertson-Day, K. Gregory, and C. Moran, 2020: Wildfire Risk to Communities: Spatial Datasets of Wildfire Risk for Populated Areas in the United States. Forest Service Research Data Archive, Fort Collins, CO. https://doi.org/10.2737/rds-2020-0060

193. Brey, S.J., M. Ruminski, S.A. Atwood, and E.V. Fischer, 2018: Connecting smoke plumes to sources using Hazard Mapping System (HMS) smoke and fire location data over North America. *Atmospheric Chemistry and Physics*, **18** (3), 1745–1761. https://doi.org/10.5194/acp-18-1745-2018

194. Sorensen, C., J.A. House, K. O'Dell, S.J. Brey, B. Ford, J.R. Pierce, E.V. Fischer, J. Lemery, and J.L. Crooks, 2021: Associations between wildfire-related $PM_{2.5}$ and intensive care unit admissions in the United States, 2006–2015. *GeoHealth*, **5** (5), 2021GH000385. https://doi.org/10.1029/2021gh000385

195. Mills, D., R. Jones, C. Wobus, J. Ekstrom, L. Jantarasami, A.S. Juliana, and A. Crimmins, 2018: Projecting age-stratified risk of exposure to inland flooding and wildfire smoke in the United States under two climate scenarios. *Environmental Health Perspectives*, **126** (4), 047007. https://doi.org/10.1289/ehp2594

196. Neumann, J.E., S.C. Anenberg, K.R. Weinberger, M. Amend, S. Gulati, A. Crimmins, H. Roman, N. Fann, and P.L. Kinney, 2019: Estimates of present and future asthma emergency department visits associated with exposure to oak, birch, and grass pollen in the United States. *GeoHealth*, **3** (1), 11–27. https://doi.org/10.1029/2018gh000153

197. Patel, S., C. Kaplan, A. Galor, and N. Kumar, 2021: The role of temperature change, ambient temperature, and relative humidity in allergic conjunctivitis in a US veteran population. *American Journal of Ophthalmology*, **230**, 243–255. https://doi.org/10.1016/j.ajo.2021.04.035

198. Anenberg, S.C., K.R. Weinberger, H. Roman, J.E. Neumann, A. Crimmins, N. Fann, J. Martinich, and P.L. Kinney, 2017: Impacts of oak pollen on allergic asthma in the United States and potential influence of future climate change. *GeoHealth*, **1** (3), 80–92. https://doi.org/10.1002/2017gh000055

199. Eguiluz-Gracia, I., A.G. Mathioudakis, S. Bartel, S.J.H. Vijverberg, E. Fuertes, P. Comberiati, Y.S. Cai, P.V. Tomazic, Z. Diamant, J. Vestbo, C. Galan, and B. Hoffmann, 2020: The need for clean air: The way air pollution and climate change affect allergic rhinitis and asthma. *Allergy*, **75** (9), 2170–2184. https://doi.org/10.1111/all.14177

200. AAFA, 2020: Asthma Disparities in America: A Roadmap to Reducing Burden on Racial and Ethnic Minorities. Asthma and Allergy Foundation of America. https://aafa.org/asthmadisparities

201. Olds, H.T., S.R. Corsi, D.K. Dila, K.M. Halmo, M.J. Bootsma, and S.L. McLellan, 2018: High levels of sewage contamination released from urban areas after storm events: A quantitative survey with sewage specific bacterial indicators. *PLoS Medicine*, **15** (7), 1002614. https://doi.org/10.1371/journal.pmed.1002614

202. Shirzaei, M., M. Khoshmanesh, C. Ojha, S. Werth, H. Kerner, G. Carlson, S.F. Sherpa, G. Zhai, and J.-C. Lee, 2021: Persistent impact of spring floods on crop loss in U.S. Midwest. *Weather and Climate Extremes*, **34**, 100392. https://doi.org/10.1016/j.wace.2021.100392

203. Uejio, C.K., M. Christenson, C. Moran, and M. Gorelick, 2017: Drinking-water treatment, climate change, and childhood gastrointestinal illness projections for northern Wisconsin (USA) communities drinking untreated groundwater. *Hydrogeology Journal*, **25** (4), 969–979. https://doi.org/10.1007/s10040-016-1521-9

204. Hoppe, B.O., K.K. Raab, K.A. Blumenfeld, and J. Lundy, 2018: Vulnerability assessment of future flood impacts for populations on private wells: Utilizing climate projection data for public health adaptation planning. *Climatic Change*, **148**, 533–546. https://doi.org/10.1007/s10584-018-2207-1

205. Alkishe, A. and A.T. Peterson, 2022: Climate change influences on the geographic distributional potential of the spotted fever vectors *Amblyomma maculatum* and *Dermacentor andersoni*. *PeerJ*, **10**, e13279. https://doi.org/10.7717/peerj.13279

206. Sonenshine, D.E., 2018: Range expansion of tick disease vectors in North America: Implications for spread of tick-borne disease. *International Journal of Environmental Research and Public Health*, **15** (3), 478. https://doi.org/10.3390/ijerph15030478

207. Hauser, N., K.C. Conlon, A. Desai, and L.N. Kobziar, 2021: Climate change and infections on the move in North America. *Infection and Drug Resistance*, **14**, 5711–5723. https://doi.org/10.2147/idr.s305077

208. Sagurova, I., A. Ludwig, N.H. Ogden, Y. Pelcat, G. Dueymes, and P. Gachon, 2019: Predicted northward expansion of the geographic range of the tick vector *Amblyomma americanum* in North America under future climate conditions. *Environmental Health Perspectives*, **127** (10), 107014. https://doi.org/10.1289/ehp5668

209. Khan, S.U., N.H. Ogden, A.A. Fazil, P.H. Gachon, G.U. Dueymes, A.L. Greer, and V. Ng, 2020: Current and projected distributions of *Aedes aegypti* and *Ae. albopictus* in Canada and the U.S. *Environmental Health Perspectives*, **128** (5), 057007. https://doi.org/10.1289/ehp5899

210. Belova, A., D. Mills, R. Hall, A. Juliana, A. Crimmins, C. Barker, and R. Jones, 2017: Impacts of increasing temperature on the future incidence of West Nile neuroinvasive disease in the United States. *American Journal of Climate Change*, **6**, 166–216. https://doi.org/10.4236/ajcc.2017.61010

211. Hoppe, B.O., L. Prussia, C. Manning, K.K. Raab, and K.V. Jones-Casey, 2023: "It's hard to give hope sometimes": Climate change, mental health, and the challenges for mental health professionals. *Ecopsychology*, **15** (1), 13–25. https://doi.org/10.1089/eco.2022.0032

212. Bjornestad, A., C. Cuthbertson, and J. Hendricks, 2021: An analysis of suicide risk factors among farmers in the Midwestern United States. *International Journal of Environmental Research and Public Health*, **18** (7), 3563. https://doi.org/10.3390/ijerph18073563

213. Cianconi, P., S. Betrò, and L. Janiri, 2020: The impact of climate change on mental health: A systematic descriptive review. *Frontiers in Psychiatry*, **11**, 74. https://doi.org/10.3389/fpsyt.2020.00074

214. Thoma, M.V., N. Rohleder, and S.L. Rohner, 2021: Clinical ecopsychology: The mental health impacts and underlying pathways of the climate and environmental crisis. *Frontiers in Psychiatry*, **12**, 675936. https://doi.org/10.3389/fpsyt.2021.675936

215. Berman, J.D., M.R. Ramirez, J.E. Bell, R. Bilotta, F. Gerr, and N.B. Fethke, 2021: The association between drought conditions and increased occupational psychosocial stress among U.S. farmers: An occupational cohort study. *Science of The Total Environment*, **798**, 149245. https://doi.org/10.1016/j.scitotenv.2021.149245

216. Liang, Y., B. Janssen, C. Casteel, M. Nonnenmann, and D.S. Rohlman, 2021: Agricultural cooperatives in mental health: Farmers' perspectives on potential influence. *Journal of Agromedicine*, **27** (2), 143–153. https://doi.org/10.1080/1059924x.2021.2004962

217. Nuako, A., J. Liu, G. Pham, N. Smock, A. James, T. Baker, L. Bierut, G. Colditz, and L.-S. Chen, 2022: Quantifying rural disparity in healthcare utilization in the United States: Analysis of a large midwestern healthcare system. *PLoS ONE*, **17** (2), e0263718. https://doi.org/10.1371/journal.pone.0263718

218. Kirby, J.B., S.H. Zuvekas, A.E. Borsky, and Q. Ngo-Metzger, 2019: Rural residents with mental health needs have fewer care visits than urban counterparts. *Health Affairs*, **38** (12), 2057–2060. https://doi.org/10.1377/hlthaff.2019.00369

219. Schultz, K., S. Farmer, S. Harrell, and C. Hostetter, 2021: Closing the gap: Increasing community mental health services in rural Indiana. *Community Mental Health Journal*, **57**, 684–700. https://doi.org/10.1007/s10597-020-00737-x

220. Hoppe, B.O., K.K. Raab, E.E. Waldhart, E.D. Waage, M.L. Varien, and J.E. Davis, 2022: Advancing Health & Disaster Resiliency in Minnesota: Co-producing Climate & Health Information for the Emergency Management Sector. Minnesota Department of Health, Minnesota Climate and Health Program, St. Paul, MN. https://www.lrl.mn.gov/docs/2022/other/221077.pdf

221. Martinich, J. and A. Crimmins, 2019: Climate damages and adaptation potential across diverse sectors of the United States. *Nature Climate Change*, **9** (5), 397–404. https://doi.org/10.1038/s41558-019-0444-6

222. Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D.J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser, 2017: Estimating economic damage from climate change in the United States. *Science*, **356** (6345), 1362–1369. https://doi.org/10.1126/science.aal4369

223. Bikomeye, J.C., S. Namin, C. Anyanwu, C.S. Rublee, J. Ferschinger, K. Leinbach, P. Lindquist, A. Hoppe, L. Hoffman, J. Hegarty, D. Sperber, and K.M.M. Beyer, 2021: Resilience and equity in a time of crises: Investing in public urban greenspace is now more essential than ever in the US and beyond. *International Journal of Environmental Research and Public Health*, **18** (16), 8420. https://doi.org/10.3390/ijerph18168420

224. Dalbotten, D.M., E. Ito, S. Eriksson, H. Pellerin, L. Greensky, C. Kowalczak, and A. Berthelote, 2017: Gidakiimanaanawigamig's circle of learning: A model for partnership between Tribal community and research university. *Interdisciplinary Journal of Partnership Studies*, **4** (3). https://doi.org/10.24926/ijps.v4i3.176

225. Ebi, K.L., J. Vanos, J.W. Baldwin, J.E. Bell, D.M. Hondula, N.A. Errett, K. Hayes, C.E. Reid, S. Saha, J. Spector, and P. Berry, 2021: Extreme weather and climate change: Population health and health system implications. *Annual Review of Public Health*, **42** (1), 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

226. Houghton, A. and C. Castillo-Salgado, 2019: Associations between green building design strategies and community health resilience to extreme heat events: A systematic review of the evidence. *International Journal of Environmental Research and Public Health*, **16** (4), 663. https://doi.org/10.3390/ijerph16040663

227. NCEH, 2022: Climate and Health: A Guide for Cross-Sector Collaboration. Centers for Disease Control and Prevention, National Center for Environmental Health. https://www.cdc.gov/climateandhealth/docs/crosssectorclimateandhealth.pdf

228. Lookadoo, R.E. and J.E. Bell, 2020: Public health policy actions to address health issues associated with drought in a changing climate. *The Journal of Law, Medicine & Ethics*, **48** (4), 653–663. https://doi.org/10.1177/1073110520979372

229. MNHSEM, 2019: Minnesota State Hazard Mitigation Plan. Minnesota Homeland Security and Emergency Management. https://dps.mn.gov/divisions/hsem/hazard-mitigation/documents/2019-mn-hmp-only.pdf

230. FEMA, 2021: 2022–2026 FEMA Strategic Plan: Building the FEMA Our Nation Needs and Deserves. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/about/strategic-plan

231. National Research Council, 2012: *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. The National Academies Press, Washington, DC, 400 pp. https://doi.org/10.17226/13165

232. NGSS, 2023: Next Generation of Science Standards [Website], accessed May 3, 2023. https://www.nextgenscience.org/

233. NSTA, 2014: National Science Teaching Association [Website], accessed May 3, 2023. https://www.nsta.org/science-standards

234. Muhich, T.E. and R.B. Rood, 2022: CCE for me: Students demand high-quality climate change course offerings. *The Science Teacher*, **90** (1). https://www.nsta.org/science-teacher/science-teacher-septemberoctober-2022/cce-me

235. Midwest CASC, n.d.: Midwest Climate Adaptation Science Center. U.S. Geological Survey, accessed August 14, 2023. https://www.usgs.gov/programs/climate-adaptation-science-centers/midwest-casc

236. ASCE, 2021: A Comprehensive Assessment of America's Infrastructure: 2021 Report Card for America's Infrastructure. American Society of Civil Engineers. https://infrastructurereportcard.org/

237. de Abreu, V.H.S., A.S. Santos, and T.G.M. Monteiro, 2022: Climate change impacts on the road transport infrastructure: A systematic review on adaptation measures. *Sustainability*, **14** (14), 8864. https://doi.org/10.3390/su14148864

238. Neumann, J.E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich, 2021: Climate effects on US infrastructure: The economics of adaptation for rail, roads, and coastal development. *Climatic Change*, **167** (3), 44. https://doi.org/10.1007/s10584-021-03179-w

239. Khatami, D. and B. Shafei, 2021: Impact of climate conditions on deteriorating reinforced concrete bridges in the US Midwest region. *Journal of Performance of Constructed Facilities*, **35** (1), 04020129. https://doi.org/10.1061/(asce)cf.1943-5509.0001528

240. Drum, R.G., J. Noel, J. Kovatch, L. Yeghiazarian, H. Stone, J. Stark, P. Kirshen, E. Best, E. Emery, J. Trimboli, J. Arnold, and D. Raff, 2017: Ohio River Basin–Formulating Climate Change Mitigation/Adaptation Strategies Through Regional Collaboration with the ORB Alliance, May 2017. Civil Works Technical Report, CWTS 2017-01. U.S. Army Corps of Engineers, Institute for Water Resources, Alexandria, VA. https://biotech.law.lsu.edu/blog/USACE-Ohio-River-Basin-CC-Report_MAY-2017.pdf

241. English, G. and D.C. Hackston, 2013: Environmental and Social Impacts of Marine Transport in the Great Lakes St. Lawrence Seaway Region: Executive Summary. Research and Traffic Group. https://greatlakes-seaway.com/wp-content/uploads/2019/10/Impacts-Comparison-ExSum.pdf

242. GLERL, 2022: The Great Lakes Dashboard. National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Great Lakes Environmental Research Laboratory, Ann Arbor, MI. https://www.glerl.noaa.gov/data/dashboard/GLD_HTML5.html

243. Environment Canada and EPA, 2009: Nearshore areas of the Great Lakes, 2009. In: *State of the Lakes Ecosystem Conference 2008*. Environment Canada and U.S. Environmental Protection Agency. https://binational.net/wp-content/uploads/2014/05/SOGL_2009_nearshore_en.pdf

244. Larson, J.H., A.S. Trebitz, A.D. Steinman, M.J. Wiley, M.C. Mazur, V. Pebbles, H.A. Braun, and P.W. Seelbach, 2013: Great Lakes rivermouth ecosystems: Scientific synthesis and management implications. *Journal of Great Lakes Research*, **39** (3), 513–524. https://doi.org/10.1016/j.jglr.2013.06.002

245. Ruswick, T., S. Burkholder, B. Davis, and M. Moffitt, 2021: Healthy Port futures: Rethinking sediments for rivermouth landscapes. *Landscape Architecture Frontiers*, **9** (3), 98–112. https://doi.org/10.15302/j-laf-1-040027

246. LCPA, 2022: More than a Port. Toledo-Lucas County Port Authority. https://www.toledoport.org/about/about-the-port/

247. Burkholder, S., B. Davis, and T. Ruswick, 2022: Ashtabula. Healthy Port Futures. https://healthyportfutures.com/project/ashtabula/

248. Craig, M.T., S. Cohen, J. Macknick, C. Draxl, O.J. Guerra, M. Sengupta, S.E. Haupt, B.M. Hodge, and C. Brancucci, 2018: A review of the potential impacts of climate change on bulk power system planning and operations in the United States. *Renewable and Sustainable Energy Reviews*, **98**, 255–267. https://doi.org/10.1016/j.rser.2018.09.022

249. Bartos, M., M. Chester, N. Johnson, B. Gorman, D. Eisenberg, I. Linkov, and M. Bates, 2016: Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States. *Environmental Research Letters*, **11** (11), 114008. https://doi.org/10.1088/1748-9326/11/11/114008

250. EIA, 2023: Electricity Data Browser. U.S. Energy Information Administration, accessed May 3, 2023. https://www.eia.gov/electricity/data/browser/

251. Austin, J. and A. Hitch, 2020: A Vital Midwest: The Path to a New Prosperity. Chicago Council on Global Affairs. https://globalaffairs.org/sites/default/files/2020-11/ccga_vital_midwest_fullissue_final_0.pdf

252. Lopez, A., A. Levine, and G. Maclaurin. 2019: U.S. Wind Siting Regulation and Zoning Ordinances. U.S. Department of Energy, National Renewable Energy Laboratory. https://doi.org/10.25984/1784284

253. Willner, S.N., A. Levermann, F. Zhao, and K. Frieler, 2018: Adaptation required to preserve future high-end river flood risk at present levels. *Science Advances*, **4** (1), 1914. https://doi.org/10.1126/sciadv.aao1914

254. Kirchmeier-Young, M.C. and X. Zhang, 2020: Human influence has intensified extreme precipitation in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (24), 13308–13313. https://doi.org/10.1073/pnas.1921628117

255. Moftakhari, H.R., A. AghaKouchak, B.F. Sanders, M. Allaire, and R.A. Matthew, 2018: What is nuisance flooding? Defining and monitoring an emerging challenge. *Water Resources Research*, **54** (7), 4218–4227. https://doi.org/10.1029/2018wr022828

256. Boustan, L.P., M.E. Kahn, P.W. Rhode, and M.L. Yanguas, 2017: The Effect of Natural Disasters on Economic Activity in US Counties: A Century of Data. Working Paper 23410. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w23410

257. Strouse, N., R.P. Herman, S.K. Sinha, and E.D. Roos, 2021: Climate Risks and Opportunities in the Great Lakes Region. Environmental Consulting and Technology, Inc., 78 pp. https://cdn.ymaws.com/www.chicagowilderness.org/resource/resmgr/publications/climaterisksgljan2021.pdf

258. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

259. Pinter, N., 2021: True stories of managed retreat from rising waters. *Issues in Science and Technology*, **37** (4), 64–73. https://issues.org/true-stories-managed-retreat-rising-waters-pinter/

260. GAO, 2020: National Flood Insurance Program: Fiscal Exposure Persists Despite Property Acquisitions. GAO-20-508. U.S. Government Accountability Office. https://www.gao.gov/products/gao-20-508

261. Pinter, N. and J.C. Rees, 2021: Assessing managed flood retreat and community relocation in the Midwest USA. *Natural Hazards*, **107**, 497–518. https://doi.org/10.1007/s11069-021-04592-1

262. GSA, 2023: Bipartisan Infrastructure Law (BIL) Maps Dashboard. General Services Administration, accessed May 4, 2023. https://d2d.gsa.gov/report/bipartisan-infrastructure-law-bil-maps-dashboard

263. Higgins, P., T. Male, and S.K. Sinha, 2021: Paying for Water Quality Improvements and Resilience in the Great Lakes: Focus on Green Stormwater Infrastructure. Environmental Consulting & Technology, Inc., 22 pp. https://www.risc.solutions/wp-content/uploads/2021/07/Paying-for-Water-Quality-Improvements-and-Resilience-in-the-Great-Lakes-A-Toolkit-for-Green-Stormwater-Infrastructure.pdf

264. Sinha, S.K., R. Pettit, J. Ridgway, J. Eidson, J. Silfen, G. Peralta, and G. Cannito, 2017: Public Private Partnerships and Finance of Large-scale Green Infrastructure in the Great Lakes Basin. Environmental Consulting & Technology, Inc., 46 pp. https://www.risc.solutions/wp-content/uploads/2020/11/Assessing-Market-Size-for-Large-Scale-Green-Infrastructure-Adoption.pdf

265. USCM and C2ES, 2022: Cities Advancing Climate Action: Leveraging Federal Funds for Local Impact: A Resource Guide. U.S. Conference of Mayors and Center for Climate and Energy Solutions. https://www.c2es.org/wp-content/uploads/2022/01/cities-advancing-climate-cation-leveraging-federal-funds-for-impact.pdf

266. Sharma, A., P. Conry, H.J.S. Fernando, A.F. Hamlet, J.J. Hellmann, and F. Chen, 2016: Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan area: Evaluation with a regional climate model. *Environmental Research Letters*, **11** (6), 064004. https://doi.org/10.1088/1748-9326/11/6/064004

267. Höök, T., C. Foley, P. Collingsworth, L. Dorworth, B. Fisher, J. Hoverman, E. LaRue, M. Pyron, J. Tank, M. Widhalm, and J. Dukes, 2018: Aquatic Ecosystems in a Shifting Indiana Climate: A Report from the Indiana Climate Change Impacts Assessment. Aquatic Ecosystems Reports, Paper 1. Purdue University, Purdue Climate Change Research Center. https://doi.org/10.5703/1288284316782

268. Kunkel, K.E., T.R. Karl, M.F. Squires, X. Yin, S.T. Stegall, and D.R. Easterling, 2020: Precipitation extremes: Trends and relationships with average precipitation and precipitable water in the contiguous United States. *Journal of Applied Meteorology and Climatology*, **59** (1), 125–142. https://doi.org/10.1175/jamc-d-19-0185.1

269. Kovacs, T. and K. Barrett, 2020: Michigan Climate Assessment 2019: Considering Michigan's Future in a Changing Climate. Michigan Climate Assessment, 1. Eastern Michigan University, Environmental Science and Society, 186 pp. https://commons.emich.edu/michigan_climate2019/1/

270. Zeng, X., P. Broxton, and N. Dawson, 2018: Snowpack change from 1982 to 2016 over conterminous United States. *Geophysical Research Letters*, **45** (23), 12940–12947. https://doi.org/10.1029/2018gl079621

271. Ashley, W.S., A.M. Haberlie, and V.A. Gensini, 2020: Reduced frequency and size of late-twenty-first-century snowstorms over North America. *Nature Climate Change*, **10** (6), 539–544. https://doi.org/10.1038/s41558-020-0774-4

272. Chen, H., J. Sun, and W. Lin, 2020: Anthropogenic influence would increase intense snowfall events over parts of the Northern Hemisphere in the future. *Environmental Research Letters*, **15** (11), 114022. https://doi.org/10.1088/1748-9326/abbc93

273. Dierauer, J.R. and C. Zhu, 2020: Drought in the twenty-first century in a water-rich region: Modeling study of the Wabash River watershed, USA. *Water*, **12** (1), 181. https://doi.org/10.3390/w12010181

274. Overpeck, J.T. and B. Udall, 2020: Climate change and the aridification of North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (22), 11856–11858. https://doi.org/10.1073/pnas.2006323117

275. Alizadeh, M.R., J. Adamowski, M.R. Nikoo, A. AghaKouchak, P. Dennison, and M. Sadegh, 2020: A century of observations reveals increasing likelihood of continental-scale compound dry-hot extremes. *Science Advances*, **6** (39), 4571. https://doi.org/10.1126/sciadv.aaz4571

276. Gautam, S., C. Costello, C. Baffaut, A. Thompson, and E.J. Sadler, 2021: Projection of future drought and extreme events occurrence in Goodwater Creek Experimental Watershed, Midwestern US. *Hydrological Sciences Journal*, **66** (6), 1045–1058. https://doi.org/10.1080/02626667.2021.1906878

277. Wu, W.-Y., M.-H. Lo, Y. Wada, J.S. Famiglietti, J.T. Reager, P.J.F. Yeh, A. Ducharne, and Z.-L. Yang, 2020: Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers. *Nature Communications*, **11** (1), 3710. https://doi.org/10.1038/s41467-020-17581-y

278. Hare, D.K., A.M. Helton, Z.C. Johnson, J.W. Lane, and M.A. Briggs, 2021: Continental-scale analysis of shallow and deep groundwater contributions to streams. *Nature Communications*, **12** (1), 1450. https://doi.org/10.1038/s41467-021-21651-0

279. USGS, 2021: Principal Aquifers of the United States. U.S. Geological Survey, accessed October 4, 2022. https://www.usgs.gov/mission-areas/water-resources/science/principal-aquifers-united-states#overview

280. Ho, J.C. and A.M. Michalak, 2020: Exploring temperature and precipitation impacts on harmful algal blooms across continental U.S. lakes. *Limnology and Oceanography*, **65** (5), 992–1009. https://doi.org/10.1002/lno.11365

281. Wilkinson, G.M., J.A. Walter, C.D. Buelo, and M.L. Pace, 2022: No evidence of widespread algal bloom intensification in hundreds of lakes. *Frontiers in Ecology and the Environment*, **20** (1), 16–21. https://doi.org/10.1002/fee.2421

282. ECCC and EPA, 2022: State of the Great Lakes 2022 Report: An Overview of the Status and Trends of the Great Lakes Ecosystem. EPA 905-R-22-001. Environment and Climate Change Canada and U.S. Environmental Protection Agency. https://binational.net/wp-content/uploads/2022/07/State-of-the-Great-Lakes-2022-Report.pdf

283. O'Reilly, C.M., S. Sharma, D.K. Gray, S.E. Hampton, J.S. Read, R.J. Rowley, P. Schneider, J.D. Lenters, P.B. McIntyre, B.M. Kraemer, G.A. Weyhenmeyer, D. Straile, B. Dong, R. Adrian, M.G. Allan, O. Anneville, L. Arvola, J. Austin, J.L. Bailey, J.S. Baron, J.D. Brookes, E. de Eyto, M.T. Dokulil, D.P. Hamilton, K. Havens, A.L. Hetherington, S.N. Higgins, S. Hook, L.R. Izmest'eva, K.D. Joehnk, K. Kangur, P. Kasprzak, M. Kumagai, E. Kuusisto, G. Leshkevich, D.M. Livingstone, S. MacIntyre, L. May, J.M. Melack, D.C. Mueller-Navarra, M. Naumenko, P. Noges, T. Noges, R.P. North, P.-D. Plisnier, A. Rigosi, A. Rimmer, M. Rogora, L.G. Rudstam, J.A. Rusak, N. Salmaso, N.R. Samal, D.E. Schindler, S.G. Schladow, M. Schmid, S.R. Schmidt, E. Silow, M.E. Soylu, K. Teubner, P. Verburg, A. Voutilainen, A. Watkinson, C.E. Williamson, and G. Zhang, 2015: Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, **42** (24), 10773–10781. https://doi.org/10.1002/2015gl066235

284. Gronewold, A.D. and R.B. Rood, 2019: Recent water level changes across Earth's largest lake system and implications for future variability. *Journal of Great Lakes Research*, **45** (1), 1–3. https://doi.org/10.1016/j.jglr.2018.10.012

285. Gronewold, A.D., H.X. Do, Y. Mei, and C.A. Stow, 2021: A tug-of-war within the hydrologic cycle of a continental freshwater basin. *Geophysical Research Letters*, **48** (4), e2020GL090374. https://doi.org/10.1029/2020gl090374

286. Millerd, F., 2011: The potential impact of climate change on Great Lakes international shipping. *Climatic Change*, **104** (3), 629–652. https://doi.org/10.1007/s10584-010-9872-z

287. Theuerkauf, E.J. and K.N. Braun, 2021: Rapid water level rise drives unprecedented coastal habitat loss along the Great Lakes of North America. *Journal of Great Lakes Research*, **47** (4), 945–954. https://doi.org/10.1016/j.jglr.2021.05.004

288. Huang, C., E. Anderson, Y. Liu, G. Ma, G. Mann, and P. Xue, 2022: Evaluating essential processes and forecast requirements for meteotsunami-induced coastal flooding. *Natural Hazards*, **110** (3), 1693–1718. https://doi.org/10.1007/s11069-021-05007-x

289. Xue, P., X. Ye, J.S. Pal, P.Y. Chu, M.B. Kayastha, and C. Huang, 2022: Climate projections over the Great Lakes region: Using two-way coupling of a regional climate model with a 3-D lake model. *Geoscientific Model Development*, **15** (11), 4425–4446. https://doi.org/10.5194/gmd-15-4425-2022

290. McKenna Jr, J.E., 2019: The Laurentian Great Lakes: A case study in ecological disturbance and climate change. *Fisheries Management and Ecology*, **26** (6), 486–499. https://doi.org/10.1111/fme.12317

291. Mason, L.A., C.M. Riseng, A.D. Gronewold, E.S. Rutherford, J. Wang, A. Clites, S.D.P. Smith, and P.B. McIntyre, 2016: Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. *Climatic Change*, **138** (1), 71–83. https://doi.org/10.1007/s10584-016-1721-2

292. U.S. Federal Government, 2022: Case Studies [Webpage], accessed September 6, 2022. https://toolkit.climate.gov/case-studies

293. NIDIS, 2023: What Is NIDIS? National Integrated Drought Information System, accessed April 27, 2023. https://www.drought.gov/about

294. NIDIS and NOAA, 2021: 2021–2024 Midwest Drought Early Warning System Strategic Action Plan. National Integrated Drought Information System and National Oceanic and Atmospheric Administration. https://www.drought.gov/documents/2021-2024-midwest-drought-early-warning-system-strategic-action-plan

295. NOAA, 2022: Runoff Risk Decision Support. National Oceanic and Atmospheric Administration, accessed October 7, 2022. https://www.noaa.gov/runoff-risk-decision-support

296. Lu, C., J. Zhang, H. Tian, W.G. Crumpton, M.J. Helmers, W.-J. Cai, C.S. Hopkinson, and S.E. Lohrenz, 2020: Increased extreme precipitation challenges nitrogen load management to the Gulf of Mexico. *Communications Earth & Environment*, **1** (1), 21. https://doi.org/10.1038/s43247-020-00020-7

297. Tewari, M., C.M. Kishtawal, V.W. Moriarty, P. Ray, T. Singh, L. Zhang, L. Treinish, and K. Tewari, 2022: Improved seasonal prediction of harmful algal blooms in Lake Erie using large-scale climate indices. *Communications Earth & Environment*, **3** (1), 195. https://doi.org/10.1038/s43247-022-00510-w

298. NOAA, 2023: NOAA Great Lakes Region. National Oceanic and Atmospheric Administration, accessed May 5, 2023. https://www.noaa.gov/regional-collaboration-network/regions-great-lakes

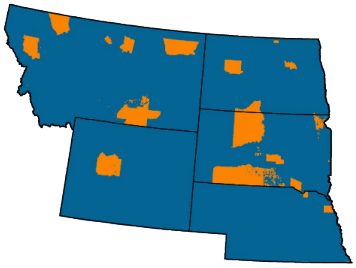
299. Makra, E. and N. Gardiner, 2021: Climate Action Plan for the Chicago Region. Metropolitan Mayors Caucus, National Oceanic and Atmospheric Administration, and U.S. Climate Resilience Toolkit. https://mayorscaucus.org/wp-content/uploads/2021/06/RegionalCAP_primary_and_appendices_062321-02.pdf

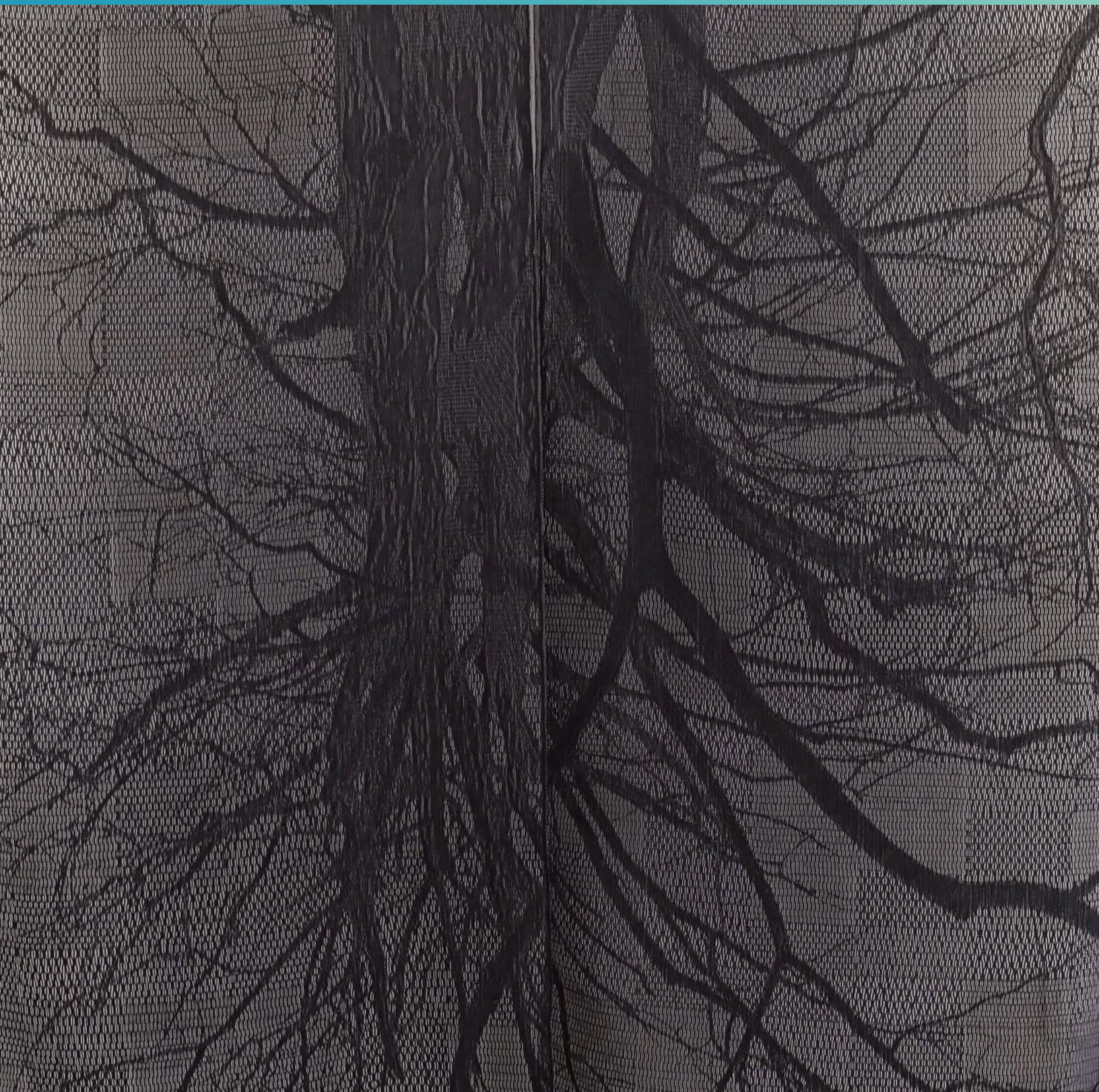
300. WICCI, 2021: Wisconsin's Changing Climate: Impacts and Solutions for a Warmer Climate. 2021 Assessment Report. University of Wisconsin-Madison, Wisconsin Initiative on Climate Change Impacts and the Wisconsin Department of Natural Resources, Madison, WI. https://wicci.wisc.edu/2021-assessment-report/

301. Seglenieks, F. and A. Temgoua, 2022: Future water levels of the Great Lakes under 1.5°C to 3°C warmer climates. *Journal of Great Lakes Research*, **48** (4), 865–875. https://doi.org/10.1016/j.jglr.2022.05.012

Fifth National Climate Assessment: Chapter 25

# Northern Great Plains





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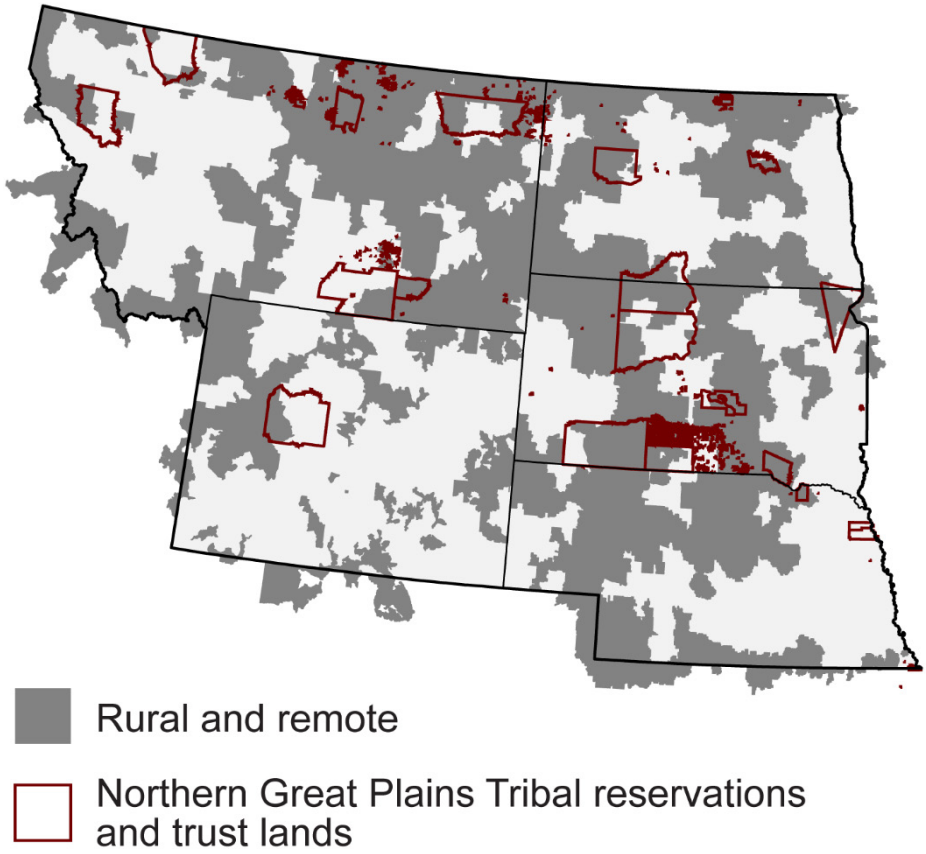
# Introduction

The Northern Great Plains region, which includes Montana, Nebraska, North Dakota, South Dakota, and Wyoming (Figure 25.1), has a wealth of natural resources supporting economies, sense of place, and leisure activities. Climate change impacts on individuals and communities will differ, and it is critical to consider equity dimensions (Ch. 20). Economic dependence on crops, rangelands, and recreation makes residents with land-based livelihoods vulnerable to climate-related changes in weather, as well as flows of water, nutrients, and wildlife across the landscape.[1,2,3] This region is largely rural, and its intact natural areas, farms, and wildlands serve as habitat for resident and migrating species, which are threatened by changing water scarcity. The region is an energy and food exporter and vulnerable to policy decisions and markets outside the region. Historical processes may lead to unequal distribution of harms, with Indigenous communities, service and energy workers, and rural residents more sensitive to impacts. Values related to place, community, and stewardship are strong. Residents of small towns express strong place attachment in comparison with their urban counterparts.[4] The region's population grew by 10% between 2008 and 2020. Ten metropolitan counties accounted for two-thirds of growth, while 75% of the region's rural counties lost population.[5] Among rural counties, energy-dependent and tourism-focused counties both grew by 14%,[6] and farm-dependent communities experienced a 3% decline in population over the same period.[7,8] An indication that more people are willing to move to the region due to climate conditions was the influx of remote workers from large cities during the COVID-19 pandemic.[9]

This region also has many vibrant Indigenous communities with a rich cultural heritage (Figure 25.1). There is increased environmental action from Indigenous communities to protect waters and lands, to navigate climate change, and to maintain cultural continuity.[10] Culturally appropriate adaptation strategies, such as the restoration of buffalo, which serve a valuable ecological role and reestablish historic relationships to landscapes, are rooted in this region.[11] "Buffalo" is the preferred term of Indigenous communities based on their culture and history; this term is used in reference to Indigenous actions while acknowledging that the scientific name of the species is American bison (*Bison bison*). Although the share of the non-White population remains small in absolute numbers, the region is becoming more culturally diverse. The Indigenous and Hispanic populations grew by 20% and 42%, respectively, between 2010 and 2019, and in 2019, Indigenous and Hispanic populations accounted for 4% and 7% of the total population.[8]

## Tribal Lands and Rurality Measures

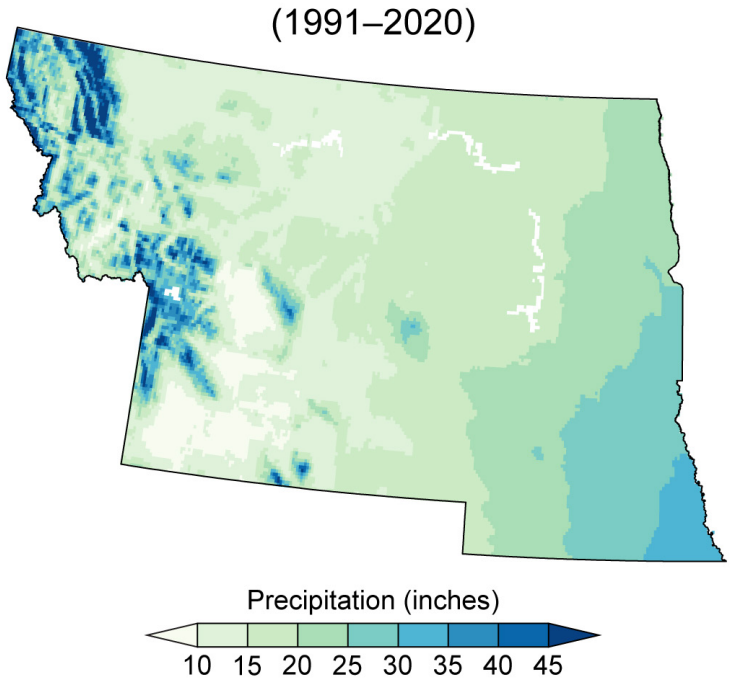



**Rural areas, including those controlled by Indigenous Peoples, are often under-resourced and therefore less resilient to climate change.**

**Figure 25.1.** Tribal reservations and American Indian trust lands (red outlines) overlap rural areas (dark gray; as defined by the USDA) across the Northern Great Plains. Rural and historically marginalized communities are often under-resourced and lack capacity to prepare for and recover from climate-driven natural disasters, making large portions of the Northern Great Plains less resilient to climate change.[12] White sections represent areas that fail to meet the criteria for "remote from urban" as defined by the USDA.[13] Figure credit: University of Wyoming, Center for American Progress, NOAA NCEI, and CISESS NC.

The Northern Great Plains region is known for its climate extremes and variability, but climate change is intensifying these characteristics.[14,15,16,17,18] The region has strong east–west precipitation (Figure 25.2) and north–south temperature gradients (Figure 25.3). Moving east to west across the region, the landscape becomes drier and elevation increases, forming three distinct areas: the humid eastern plains, semiarid high plains, and mountainous west. This complexity makes it challenging to summarize climate impacts across the region, but there are some common changes. Climate extremes in this region are expected to continue, compounded by climate change (KM 25.1). Human and ecological health will be impacted by these compounding hazards (KM 25.2). Human communities reflect the dependence on natural resources, historical policy legacies, and market forces that left a patchwork of land ownership and use (such as crop versus range, energy development, and recreation; Figure 25.8), and these livelihoods are at risk (KM 25.3). Climate change response will involve navigating complex tensions and trade-offs (KM 25.4), but communities are already building their capacity to adapt and transform (KM 25.5).

### Average Precipitation for the Northern Great Plains




**The region has distinct east–west precipitation gradients.**

**Figure 25.2.** The map shows annual precipitation averaged over 1991–2020. Distinct precipitation gradients are evident from east to west and with elevation. These gradients highlight the complexity of the climate across the Northern Great Plains. White areas are large water bodies. Figure credit: USGS, University of Wyoming, NOAA NCEI, and CISESS NC.

## Key Message 25.1

## Climate Change Is Compounding the Impacts of Extreme Events

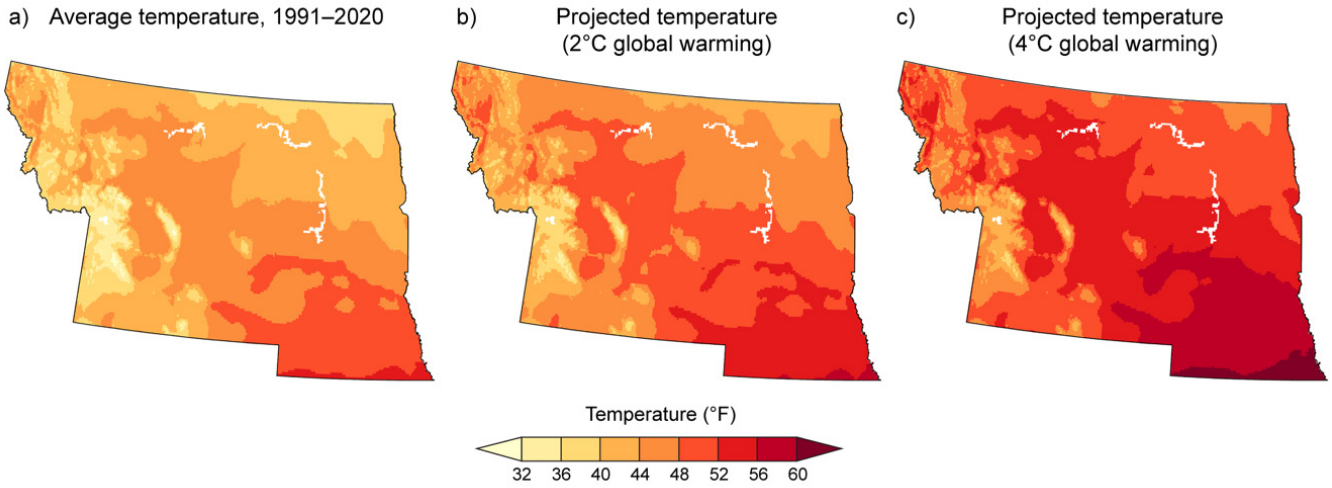
The Northern Great Plains region is experiencing unprecedented extremes related to changes in climate, including severe droughts (*likely*, *high confidence*), increases in hail frequency and size (*medium confidence*), floods (*very likely*, *high confidence*), and wildfire (*likely*, *high confidence*). Rising temperatures across the region are expected to lead to increased evapotranspiration (*very likely*, *very high confidence*), as well as greater variability in precipitation (*very likely*, *high confidence*).

### *Temperatures and Precipitation*

Given the frequency of extremes and weather variability in the region, it is challenging to quantify long-term climate change trends. Even so, significant temperature trends and projections are clear (Figure 25.3). Since 1900, annual average temperature has increased in the region by 1.6°–2.6°F, with the largest increase in North Dakota and the smallest increase in southern Nebraska. Warming has occurred in all seasons but is most pronounced in winter. Summers have warmed little in North Dakota, South Dakota, and Nebraska. However, warm nights (minimum temperature of 70°F or higher), which were once rare, have become more common in Montana and Wyoming. The region has experienced fewer very cold days (maximum temperature of 0°F or lower) than the long-term average (1900–2020) for several decades. For

instance, the number of very cold days has been below the long-term average in Montana since 1985, in Nebraska since 1990, and in Wyoming, North Dakota, and South Dakota since 2000.[14,15,16,17,18] Decreasing snowpack will alter surface water availability for irrigation and may increase pressure on groundwater resources.[3,19] Overall aridity has increased and is projected to continue to do so because of increases in potential evapotranspiration, suggesting that the demarcation line between the humid East and arid West, traditionally defined by the 100th meridian, is moving eastward.[20,21]

## Temperature for the Northern Great Plains




**Distinctive gradients of temperature will hold with projected warming.**

**Figure 25.3.** The maps show temperature averages for 1991–2020 (**a**) and projected temperature for global warming of 2°C (3.6°F; **b**) and 4°C (7.2°F; **c**) above preindustrial levels for the Northern Great Plains region. Current and projected values demonstrate distinctive gradients of temperature from southeast to northwest, with implications for climate impacts and effective adaptation. White areas are large water bodies. Figure credit: USGS, NOAA NCEI, CISESS NC, and University of Wyoming. See figure metadata for additional contributors.

All states in the Northern Great Plains region recorded their wettest five-year period between 1995 and 2019.[14,15,16,17,18] Total annual precipitation will be relatively stable across the region (Figure 4.3), but shifts in the form and timing of precipitation are expected. More intense precipitation events highlighting the projected increased variability in precipitation are expected to occur in all seasons, especially in the spring (Figure 2.12).[22] Temporal and spatial variability continues to be a dominant factor with precipitation and temperature.

Much of the runoff in the Northern Great Plains region contributes to the Missouri River and eventually the Gulf of Mexico, but portions contribute to the Columbia River, Colorado River, and Red River of the North basins. Much of the increasing streamflow in North Dakota shown in Figure 25.4 occurs in the Red River of the North basin and has prompted an approximately $3.2 billion (in 2022 dollars) infrastructure project to divert flood water around Fargo, North Dakota, and Moorhead, Minnesota.[23] The upper Colorado River basin (Colorado, Wyoming, Utah, and New Mexico), with headwaters in the western Northern Great Plains region, has been experiencing extensive drought for the last 20 years. Flows in the upper Colorado River basin, which account for about 90% of the streamflow of the entire basin,[24] have decreased over the past 20 years.[25,26] Increases in evaporative demand (the loss of water from Earth's surface to the atmosphere; Figure 25.5) have decreased runoff efficiencies, meaning that less rain and melted snow end up reaching the streams that feed the Colorado River.[27] Model-based analysis shows that continued warming is expected to further reduce flows in the upper Colorado River basin.[26]

## Hail

The region is prone to damaging hailstorms; southeastern Wyoming and the southwestern part of the Nebraska Panhandle lie in "hail alley," the most hail-prone area in the United States.[17,18] Changes in low-level moisture, convective instability, melting level height, and wind shear will create shifts in hail occurrence.[28] From 1979 to 2017, the number of days favorable to significant (2 inches or greater diameter) hail in the central and eastern United States increased by 2 to 4 days each year.[29]

Research on the response of severe convection to climate change has focused on a very high scenario (RCP8.5).[30,31,32,33] Hail size, frequency of large hail, and length of hail season are projected to increase through the rest of this century in the Northern Great Plains.[33] By 2071–2100, under a very high scenario (RCP8.5), projections for the Northern Great Plains show a 27% increase in moderate-size (0.79–1.4 inches) hail days, a 49% increase in large (1.4–2.0 inches) hail days, and a 302% increase in very large (2 inches and larger) hail days, with increases in hail coverage of 73%, 157%, and 882% for moderate, large, and very large hail, respectively.[33] Projections also indicate a lengthened hail season.[33] The largest increases in hail risk anywhere in the United States are in this region and in July.[33] Projections by late this century using the SRES (Special Report Emissions Scenarios) A2 scenario (a scenario with increasing greenhouse gas emissions, similar to those in RCP8.5) indicate more hail days and an increase in the potential size, with a correspondent increase in accumulated kinetic energy and damage potential.[34] Comparing intermediate (RCP4.5) and very high (RCP8.5) scenario projections for severe convection indicates that the projected trends for RCP4.5 are in the same direction with lower amplitude compared to RCP8.5.[35]

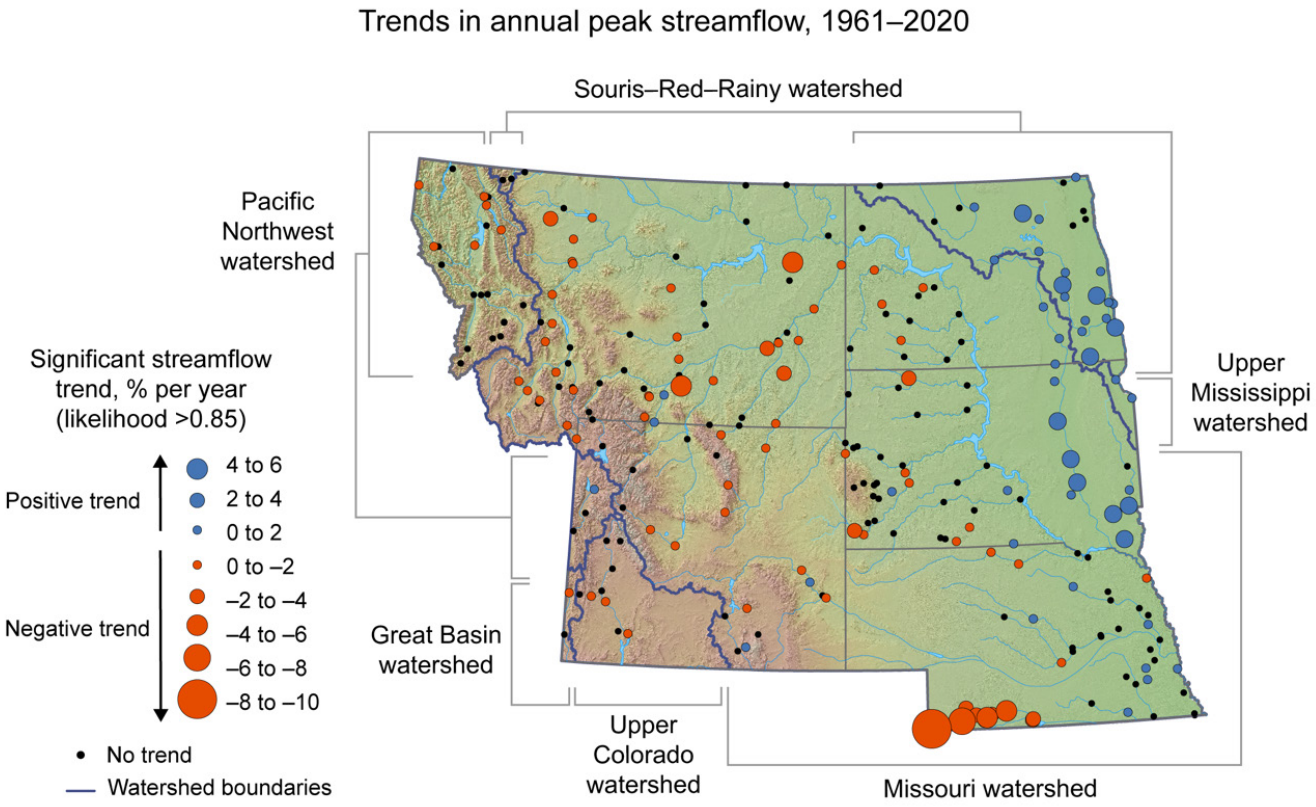
## Flooding

Precipitation changes do not have a one-to-one relation with flooding. Many factors influence floods, including short- and long-term antecedent moisture conditions, presence of frozen soils, snowpack accumulation, rain-on-snow events, storm tracks, and rainfall rates.[36,37,38,39]

The Missouri River transects the region through 10 US states and 28 Tribal territories and is emblematic of the complex intergovernmental relations that will become increasingly important under climate change.[40] Record floods along the Missouri River and its tributaries in 2011 and 2019 caused evacuations, cost billions in damages,[41] and created interstate closures. Research suggests that recent large floods were caused by natural variability within the system;[42] however, model simulations suggest that climate change will reduce runoff in the upper Missouri basin.

Trends in annual peak streamflow, a proxy for flooding, differ across the 100th meridian divide (Figure 25.4). Observations show that annual peak streamflow is decreasing in the west and increasing in the east.[43] With few exceptions, the eastern Dakotas are an area of increasing peak streamflow (and flooding), while the western Dakotas, Montana, and Wyoming have decreasing peak streamflow. With 2° to 4°C (3.6° to 7.2°F) of global warming, the Northern Great Plains would expect to see some of the highest increases in annual flooding damage costs in the contiguous US due to climate change.[44]

## Water Resource Regions and Rivers



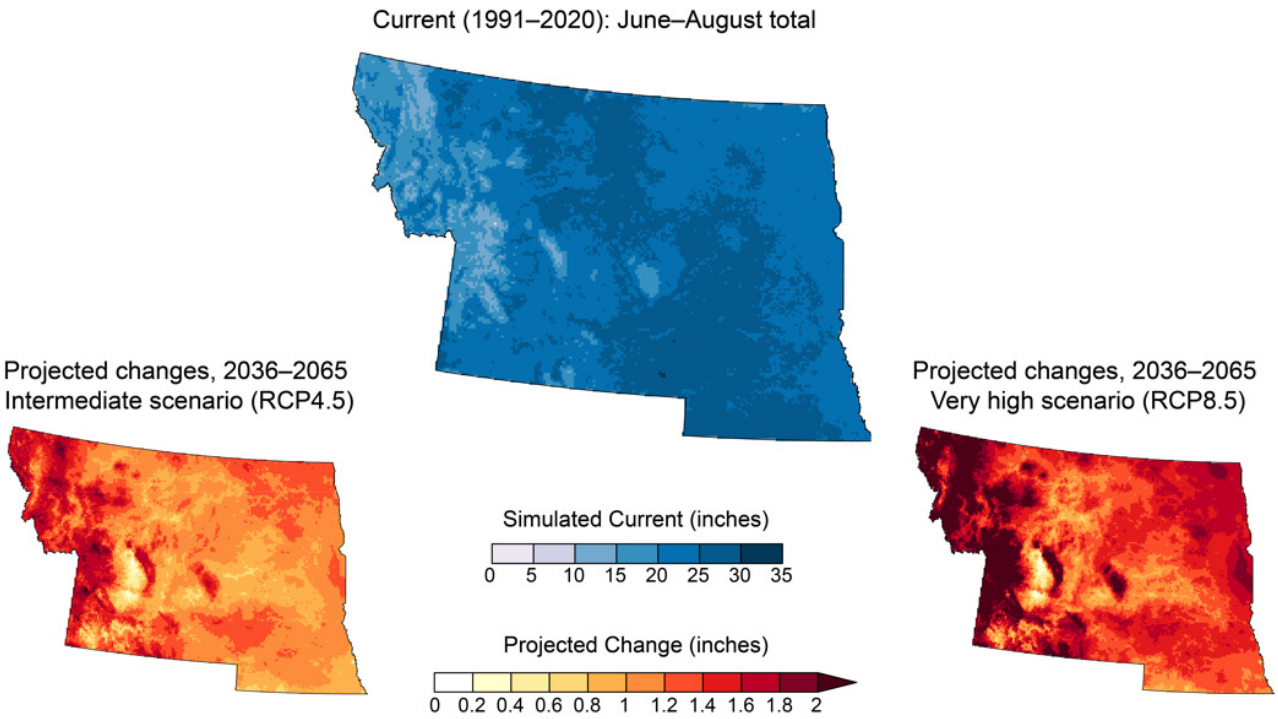

**Annual peak streamflow—a proxy for flooding—has been rising in eastern portions of the region and declining in the west.**

**Figure 25.4.** This map of the water resource regions and rivers within the region shows distinct east–west differences in trends in annual peak streamflow for 1961–2020, expressed as percent per year, where the size of the dot is relative to the size of the trend. Red dots are downward trends, and blue dots are upward trends. A likelihood-based approach is used to report these trend results. When a trend is identified, the trend likelihood value (likelihood = 1 – p-value/2) associated with the trend is between 0.85 and 1.0. In other words, the chance of the trend occurring in the specified direction is at least 85 out of 100. Smaller black dots are sites for which there were sufficient data for trend analysis but likelihood was less than 0.85; that is, these sites do not exhibit a substantial trend in either direction. Figure credit: USGS, NOAA NCEI, and CISESS NC.

## *Drought*

Drought is projected to increase in the region, with localized droughts increasing by 2040 and more widespread regional droughts by 2070, under intermediate (RCP4.5), high (RCP6.0), and very high (RCP8.5) scenarios across wet or dry global climate models.[22,45] After precipitation, the most significant component of the water budget is evapotranspiration—the moisture transfer from Earth's surface and plants to the atmosphere.[46] Projected warming is expected to increase evapotranspiration (Figure 25.5), which may lead to drier soils later in the growing season (Figure 25.6).[47,48,49] Summer drought will be more probable than spring drought.[22,50] Multiple future climate scenarios indicate future increases in moderate, severe, and extreme drought, occurring approximately 10% and 20% more frequently by 2050 and 2100, respectively.[45] Recent droughts in the upper Missouri River basin between 2000 and 2010 were the most severe in the instrumental record,[51] and flash droughts are a growing concern.[52,53]

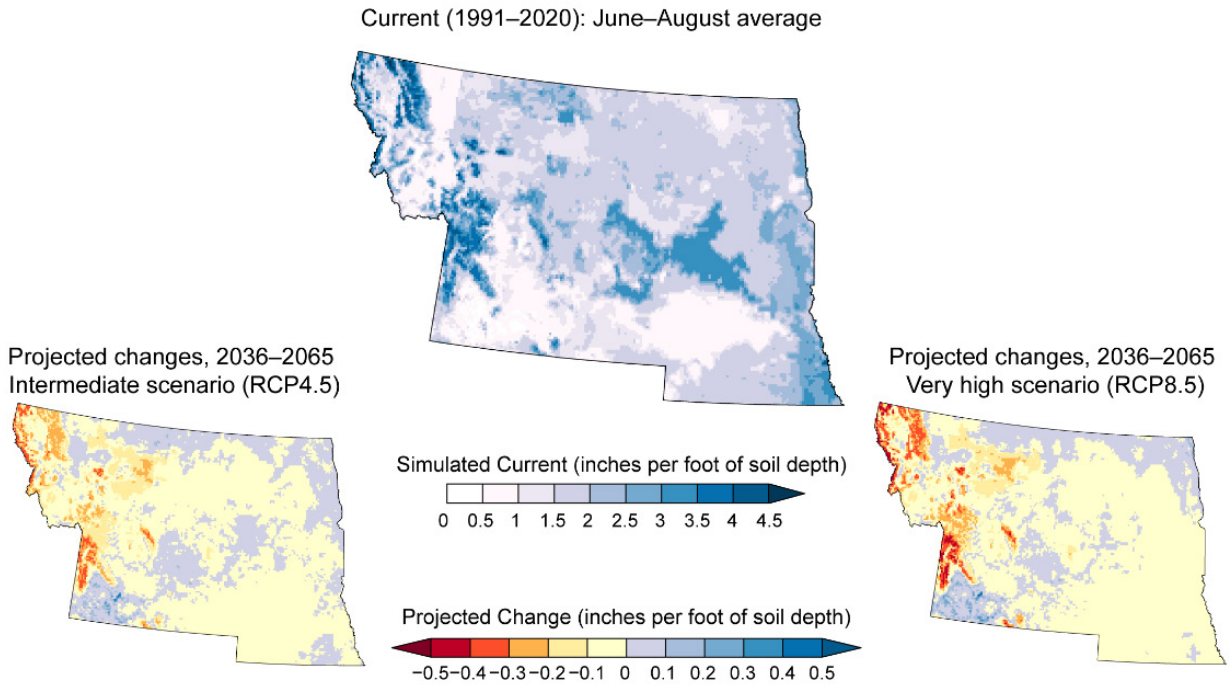
## Current and Projected Potential Evapotranspiration




**Warming is expected to increase evapotranspiration.**

**Figure 25.5.** Figure shows (**center**) simulated current evapotranspiration and its projected change for the summer months under (**left**) intermediate and (**right**) very high scenarios. Data presented were obtained from Variable Infiltration Capacity models driven by the Coupled Model Intercomparison Project Phase 5 and Localized Constructed Analogs downscaling methods. Potential evaporative demands in the summer months (June, July, and August) increase regionally, especially in western areas under moderate climate change, and in both western and eastern areas under severe climate change. An increase in potential evapotranspiration typically drives a decrease in surface soil moisture (4-inch depth; Figure 25.6). Figure credit: USDA Forest Service, NOAA NCEI, and CISESS NC. See figure metadata for additional contributors.

## Current and Projected Soil Moisture




**Warming may not always lead to declines in soil moisture that would cause water stress in crops and natural plants.**

**Figure 25.6.** Figure shows (**center**) simulated current soil moisture and its projected change for the summer months under (**left**) intermediate and (**right**) very high scenarios. Data presented were obtained from Variable Infiltration Capacity models driven by the Coupled Model Intercomparison Project Phase 5 and Localized Constructed Analogs downscaling methods. Soil moisture is expected to decrease slightly throughout the region in the summer months, with the largest decreases in the western mountain ranges of Montana. An increase in southwestern Wyoming is projected under both intermediate and very high scenarios. Snow water equivalent is decreasing at higher elevations in the Northern Great Plains (Figure 4.5) and can contribute to lower soil moisture in these areas. Declines in soil moisture can lead to crop, forest, and rangeland plant water stress, reduce plant growth, and increase ecosystems' susceptibility to fire. Figure credit: USDA Forest Service, NOAA NCEI, and CISESS NC. See figure metadata for additional contributors.

## *Wildfire*

Driven by increased temperature and decreased relative humidity, fire potential in this region is projected to increase under future climate change (HadCM3-HRM3 model), especially in summer and autumn, with fire seasons becoming longer.[54] Increased evapotranspiration and drought risk raise the probability of large fire occurrence.[55,56] The number of large grassland wildfires in the four semiarid ecoregional grasslands of the Northern Great Plains increased by 213%, from 128 between 1985 and 1995 to 273 between 2005 and 2014, with total area burned increasing in the western ecoregions of the region by 350% but decreasing in eastern ecoregions by 75% or more.[57] Wildfire numbers and fire-season length increased from the 1970s to the 2000s by 889% and 85 days, respectively, in western Montana and Wyoming forests, with most ignited by lightning strikes rather than humans.[58] Historically, snow cover prevented winter wildfires and increased fuel moisture conditions during snowmelt followed by spring precipitation.[59,60] However, early spring snowmelt has been correlated with increased fire activity.[58] From 1950 to 2010, the number of snow-cover days declined within the region,[60] increasing wildfire activity due to drying fuels, which can lead to changes in flash flooding and debris flow (Focus on Western Wildfires).

## Key Message 25.2

## Human and Ecological Health Face Rising Threats from Climate-Related Hazards

Climate-related hazards, such as drought, wildfire, and flooding, are already harming the physical, mental, and spiritual health of Northern Great Plains region residents (*virtually certain*, *high confidence*), as well as the ecology of the region (*very likely*, *medium confidence*). As the climate continues to change, it is expected to have increasing and cascading negative effects on human health and on the lands, waters, and species on which people depend (*very likely*, *medium confidence*).

### *Mental Health*

Climate change adversely affects mental and spiritual health in multiple ways (Ch. 15).[61,62] Although this issue affects the entire country, it is especially relevant in the Northern Great Plains, where three states are among the top 10 in highest suicide rates per capita in the Nation.[63] Suicide rates are particularly high in rural and Indigenous populations,[64] in part because of remoteness from care and the limited number of mental health professionals.[65,66] Based on geographically broad-based studies, climate change is projected to amplify these risks.[67,68] Climate anxiety, also called eco-anxiety (a feeling of doom about future climate change), is already prominent among farmers and ranchers in the region.[69] Solastalgia—the distress specifically caused by environmental change while still in a home environment[70,71]—is indicative of more subtle but potentially wider-reaching mental health impacts. Solastalgia is most often associated with Indigenous communities, who share collective ancestral ties to the lands and natural resources where they live or previously lived and which are inextricably linked to their identities, cultures, and livelihoods, as well as their physical and spiritual well-being.[72] However, solastalgia can also affect others who are connected to the land, such as ranchers and farmers.[73]

Direct impacts such as crop failure, increased disease, and biodiversity loss can lead to increased loss of Traditional Knowledge and language, further influencing the mental health of Indigenous Peoples.[61,74] Despair related to the loss of environmental, cultural, and human health is widespread among Crow Tribal elders, adversely affecting mental and spiritual health, and is exacerbated by a sense of inability to address the root causes of climate change.[75,76]

### *Physical Health*

Climate change is impacting the physical health of the region's inhabitants in a number of ways. Wildfire is projected to increase in the region (KM 25.1), with correspondent health and property implications (Chs. 14, 15; Focus on Western Wildfires).[61] One study suggests that although the total number of premature deaths attributable to wildfire smoke is higher in states with greater population density, Montana has the highest per capita rate of such deaths in the country.[77] In addition, heat is responsible for more climate-related deaths than any other factor in the United States.[78] Although the Northern Great Plains region lacks the extreme temperature increases experienced in some other regions, people in this region are still at risk given the large number of outdoor workers and recreationists.[79] Rising temperatures, as well as other climate impacts, are expected to increase the risk of some vector-borne diseases, such as West Nile virus.[80,81,82] Flood risk patterns in the United States are inequitable on a county basis, with some of the counties in this region at increased risk, including some that encompass or are adjacent to Tribal reservations.[83] Shifts in precipitation and increased flooding (KM 25.1) are expected to raise the risk of water-borne diseases such as *Campylobacter* infection.[84]

## Compound Health Impacts of Climate Events

Multiple climate pressures frequently act simultaneously, leading to compounding health-related outcomes (Ch. 15).[61,85,86] The impacts of floods resulting from earlier snowmelt combined with more intense precipitation events can be worsened by loss of ground cover from past wildfires,[87] putting people at risk of water-borne diseases, trauma and increased mental health issues, and economic losses. Wildfires are more common during hotter months when drought is more common,[55,56] exposing people to compounding risks and stress from smoke, heat, and poor water quality.[88,89]

## Ecological Health

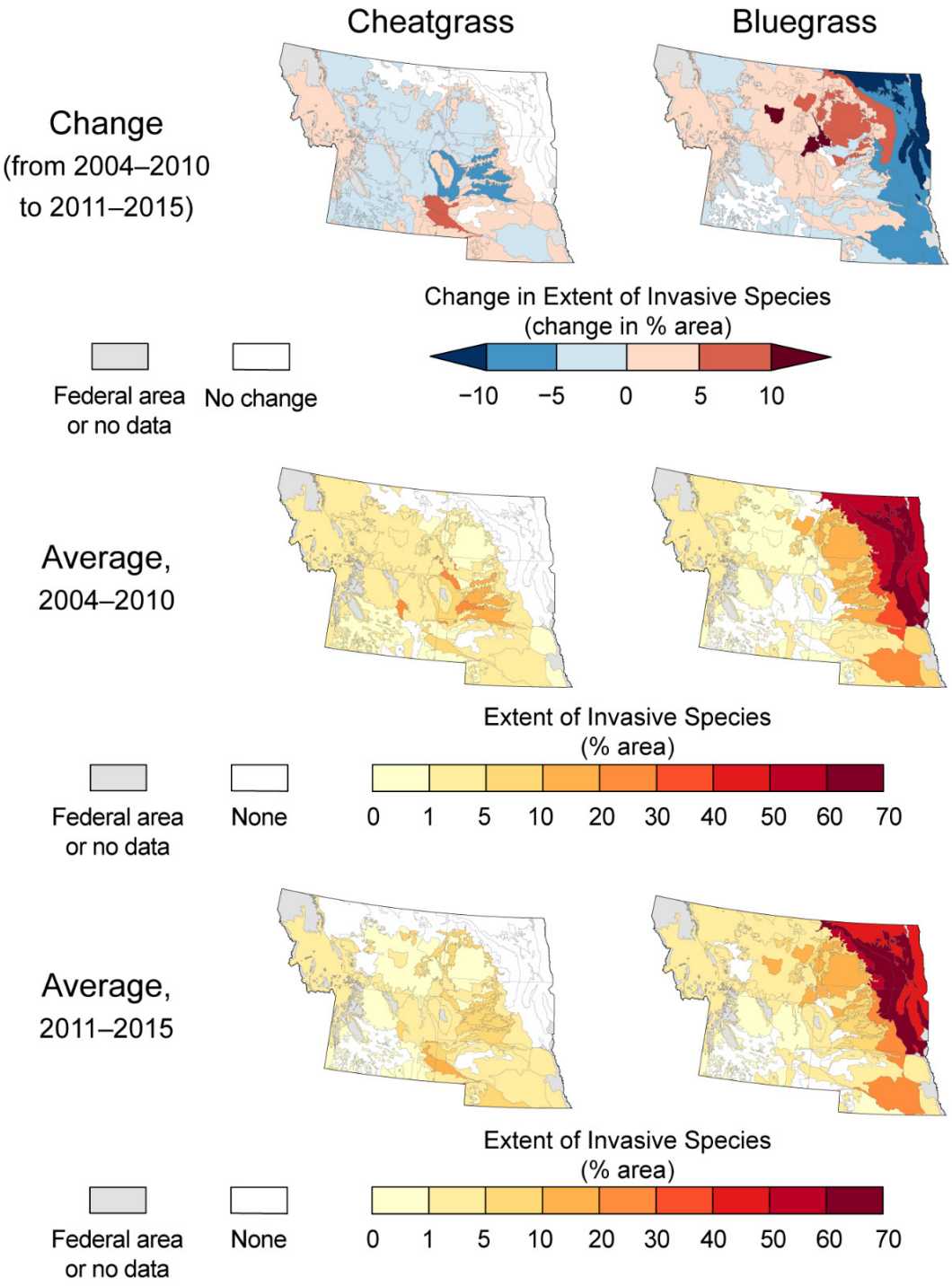
### Water Quality

Excess contributions of nutrients, such as nitrogen and phosphorus from agricultural runoff or point sources such as wastewater treatment plants, can cause water quality issues, which are expected to be exacerbated by climate change.[90,91] Nutrient loads (the total amount of a nutrient transported past a single location over a set period of time) can increase after droughts, when sediment is flushed in subsequent runoff events.[92] Nutrient runoff from agricultural land spikes after heavy rain and contributes to harmful algal blooms and transport of nutrients to the Gulf of Mexico (KM 25.5).[93,94,95] Climate change has long been hypothesized as a driver of harmful algal blooms;[96] supporting these hypotheses with observations has been challenging because of gaps in monitoring, lack of long-term algae data, and changes in laboratory and remote-sensing methods.[97,98]

### Cascading Impacts to Biodiversity Loss

Climate change compounds existing threats to biodiversity (Ch. 8). Within the Northern Great Plains, conversion of perennial grasslands to monocultures of annual crops results in a loss of biodiversity.[99] Invasive species are also a contributor to biodiversity loss in the region,[100,101] and the dominant invasive species of concern varies from east to west (Figure 25.7). The region is a hotspot for grassland bird diversity and encompasses the entire breeding season range for many of the most vulnerable species;[102,103] based on projections under a scenario with 5.4°F (3.0°C) warming above preindustrial levels, more than 80% of grassland bird species will be vulnerable to climate-related threats during the breeding season.[104] Both native pollinators and honeybees are important components of the region's ecosystems. The region supports approximately 40% of US honeybee colonies in the summer.[105] Over the last 15 years, pollinators have been experiencing declines.[106] Although not directly linked to climate change, changes in land-use patterns related to biofuel policies and loss of Conservation Reserve Program (CRP) lands are potentially contributing to these declines.[105,107] The CRP program pays farmers to take marginal land out of agricultural production for 10 years and plant perennial cover to reduce soil erosion and provide other ecosystem benefits. Recent modeling, however, indicates that targeting where CRP lands are planted on the landscape could improve the benefits to pollinators.[108] Finally, natural resource managers have identified a number of management strategies to help reduce biodiversity loss in the face of climate change, but for many taxa and ecological communities, there are still knowledge gaps.[109,110]

## Invasive Species as Bioindicators of Ecological Condition




**Invasive cool-season grasses are reducing biodiversity in the Northern Great Plains.**

**Figure 25.7.** Acreage in the Northern Great Plains region where at least 50% of the soil surface is covered by two representative invasive plant species: cheatgrass (*Bromus tectorum*; **left**) in the western part of the region, and Kentucky bluegrass or Canada bluegrass (*Poa pratensis* or *Poa compressa*; **right**) in the eastern part of the region. The figure shows acreage for 2004–2010 (**center**) and 2011–2015 (**bottom**), as well as the change in extent of invasion between those two periods (**top**). These invasive grasses already pose a threat to the biodiversity of the region, and climate change is predicted to increase invasive species challenges for this region. Figure credits: (center left, bottom left, center right, bottom right) adapted from NRCS 2018;[111] (top left, top right) The Nature Conservancy, NOAA NCEI, and CISESS NC.

## Key Message 25.3

## Resource- and Land-Based Livelihoods Are at Risk

The Northern Great Plains region is heavily reliant on agriculture and resource-based economies, placing livelihoods at risk from the impacts of climate change and related policy. Agriculture and recreation will see some positive effects but primarily negative effects related to changing temperature and precipitation regimes (*likely*, *medium confidence*). Energy-sector livelihoods will be affected as emissions-reductions policies drive shifts away from fossil fuel sources (*likely*, *high confidence*). Climate change is expected to test the adaptive resilience of the region's residents, in particular rural, Indigenous, and low-income immigrant populations (*likely*, *medium confidence*).

### *Food and Agriculture*

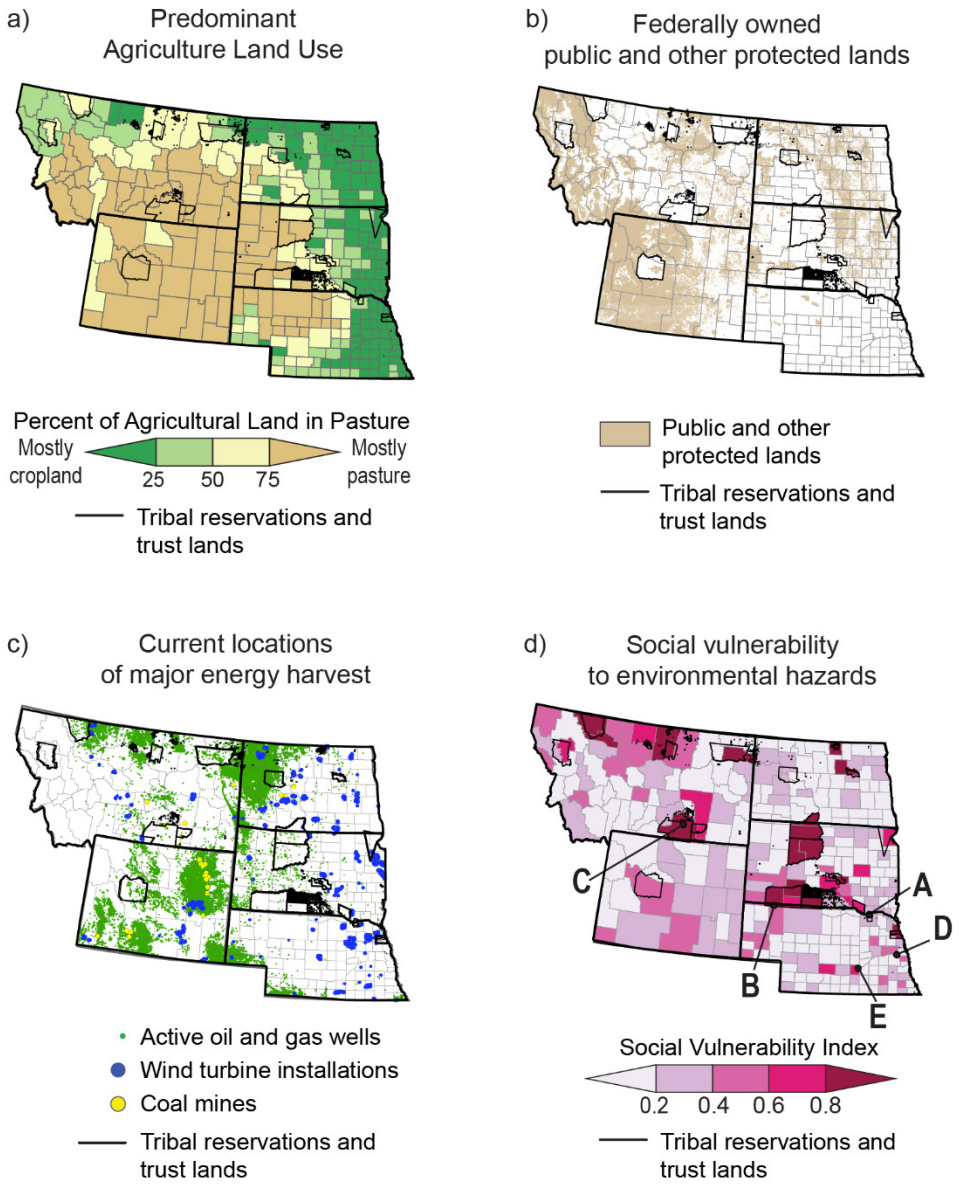
Farming (referring to all forms of agricultural production, including livestock operations) accounts for 6% of total earnings in the region, compared to 0.4% of total earnings nationally.[112] Although growing seasons and frost-free periods are lengthening,[113,114] other factors may stress crop production.[49] Negative crop yield impacts are anticipated from rising temperatures, which increase the potential for heat and moisture stress during reproductive periods, as well as the potential for increased weed competition and pest expansion.[3] Although row crop agriculture generally occurs where greater average annual precipitation occurs (Figures 25.2, 25.8a), farmers are expanding and intensifying croplands into less productive lands in the region[99,115,116] as climate change alters growing conditions. Although crop yield decline from increased evapotranspiration may be somewhat offset by soil moisture trends, soil moisture is projected to slightly decline on an annual basis across much of the region (KM 25.1).[117,118] Overwintering crops like winter wheat are expected to benefit from reduced exposure to frost days under climate change, but reduced ground insulation from declining snow cover may offset some of this gain.[119] Additionally, higher carbon dioxide concentrations are expected to benefit the productivity of many crops.[120]

The net effect of climate change on specific crop yields is uncertain and will depend on interacting effects of temperature, moisture, carbon dioxide, and ozone, as well as adaptation through shifts in cultivars, crop mix, and management practices.[120,121,122] For example, climate change was listed as a primary challenge to both dryland and irrigated agriculture in the 2022 Blackfeet Agricultural Resource Management Plan (ARMP), due to earlier snowmelt, increased evapotranspiration, and less water available for irrigation. Recent extreme events indicate potential future impacts to livelihoods of individuals throughout the agricultural value chain.[123] Climate change negatively impacts the ability of regional Indigenous communities to grow and use traditional foods, medicines, and plants due to species movements and shifts in growing and harvesting seasons. Two significant examples are the Lakota staples wild turnips and chokecherries.[124,125] In 2017, above-normal temperatures in late summer and fall delayed the harvest of berries and medicinal plants.[126]

Northern Great Plains rangeland productivity may see less harm from climate change than other livestock-producing regions.[127,128] Rising temperatures and elevated carbon dioxide levels are projected to increase growing-season length and carbon assimilation by plants, thus increasing aboveground net primary productivity (atmospheric carbon converted into aboveground plant matter)[129,130,131] but decreasing nutritional quality.[132,133] However, drought-induced water limitation would produce the opposite response by reducing biomass production, concentrating nutrients, and enhancing forage quality.[134] While the northern part of the region could see more frequent forage surpluses under both intermediate (RCP4.5) and very high (RCP8.5) scenarios, the southern part of the region (e.g., Nebraska) may experience more frequent forage deficits.[1] Drought years have had a smaller impact on cattle numbers in the Northern Great Plains than

in other regions,[135] and single-year droughts have only minimally impacted management or livelihoods.[136] However, ranchers face increasing challenges managing livestock health due to heat stress, parasites, and pathogens, as well as managing shifts in forage species, including invasive weeds.[137,138] Tribal producers may be more vulnerable to these stresses, as they tend to operate smaller farms and ranches on lands that have highly fractionated ownership, compared to non-Indigenous producers.[139] While cattle production has moved northward overall,[1] additional stressors to rangeland-based livelihoods exist in the region, including conversion to cropland,[140] rising land prices, and land ownership concentration trends.[141,142,143]

## Geography of Land Use and Social Vulnerability




**The Northern Great Plains region shows wide geographical variations in land use and social vulnerability.**

**Figure 25.8.** The figure shows the geography of resource- and land-based livelihoods and vulnerabilities. Tribal reservation and trust lands are outlined on all maps. Panel (**a**) displays the predominant use of each county's agricultural land as either pasture or cropland. Pasture is common throughout much of the region, with cropland prev-

alent in the eastern portion of the region. Panel (**b**) shows federally owned public lands, including lands managed by the National Park Service, Bureau of Land Management, Bureau of Reclamation, US Forest Service, US Fish and Wildlife Service, Department of Defense, Department of Energy, and other federal agencies. In addition to public lands, private protected areas voluntarily provided to the database are also included but make up a very small minority of the overall public and other protected land area. The amount of federally owned public land increases in the more arid western portion of the region. Panel (**c**) displays locations of major energy sources in the region. Surface coal mines, oil and gas wells, and wind turbine installations are located throughout the region. Panel (**d**) shows county-level Social Vulnerability Index (SoVI) scores, with higher scores closer to 1 indicating higher levels of social vulnerability to environmental hazards.[144] Capital letters in panel (d) display locations of recent extreme climate events highlighted in the "Community Infrastructure and Quality of Life" section below (A, D, and E highlight examples of flood impacts, B highlights storm damage, and C provides an example of drought impacts). Figure credit: University of Nebraska, USDA Forest Service, NOAA NCEI, and CISESS NC.

## *Tourism and Recreation*

The region's public and private lands provide tourism revenue, as well as benefits to residents' quality of life (Figure 25.8b).[145,146] Climate-related trends and extremes are expected to affect ecosystem services, wildlife, and tourism, with associated economic impacts.[147,148] Higher temperatures in the Yellowstone River in August 2016 are blamed for a fish kill that triggered the closure of the river to fishing and other uses, decreasing income for local and regional businesses.[149] Water-based activities are particularly vulnerable to drought and face increased conflicts with other water uses.[150] In 2017, Montana lost approximately 800,000 visitors and $289 million (in 2022 dollars) of tourism- and recreation- related income due to drought.[151] Visitors also shortened their stays due to smoke and fires.[150] Warmer winter temperatures in recent decades are correlated with mountain pine beetle outbreaks in western Montana but were not significantly correlated with mountain pine beetle outbreaks in other forests within the region, such as the Black Hills.[152] A 2017 drought decreased pheasant populations, affecting tourism income; its impact on wildlife populations also reduced Tribal-guided hunting opportunities and may have affected the competitiveness of culturally significant plants.[126] The length of winter sports seasons is expected to decrease[153] and thus negatively affect recreation economies in Montana, Wyoming, and South Dakota.[154] However, there may be improved opportunities for spring and autumn "shoulder season" recreation and both positive and negative effects on wildlife-based activities.[150]

## *Energy*

Energy revenue in the region supports local services, infrastructure, and income that includes per capita payments for some Tribal members.[155] Energy revenue can also create risks in the region stemming from short-term revenue volatility and long-term dependence.[156] The region has an extensive number of oil and gas wells, numerous surface coal mines, and increasing wind turbine installations (Figure 25.8c). The region's share of employees working in fossil fuel extraction is four times greater (1.8% of all jobs) than in the Nation as a whole (0.4% of all jobs).[5] Energy-related livelihoods are affected by climate change due to changes in power generation, transmission, and consumption, as well as shifts in demands for particular types of energy sources.

Climate change impacts and mitigation efforts are expected to change energy demand in the Northern Great Plains seasonally. Higher summer temperatures and heatwaves are expected to increase energy demand in the Northern Great Plains and throughout the country, while in the region, higher winter temperatures and fewer cold snaps are expected to reduce energy demand for heating (Ch. 5).[157,158] Increased energy demands from outside the region will place increased demands on regional energy resources and electricity supply.[159] Lower winter electricity demands may potentially lower annual household energy costs in this region,[157] but increased electrification of the grid may increase costs to utility ratepayers as natural gas utilization declines.[160] Finally, climate change, especially climate extremes, may also stress energy infrastructure (e.g. rail, pipelines, distribution lines, transmission lines; Ch. 5).[161,162]

Energy-related livelihoods are also affected by shifts in the type of energy harvested. Energy extraction and generation in the region respond to external market and policy drivers.[163,164,165] For example, coal extraction has declined since 2011 due to air quality regulations, competition with lower-cost natural gas and renewables, and climate policy in states and utilities outside the region.[155] Tribal and other rural communities dependent on coal extraction for revenue and jobs have experienced losses to both as markets shift away from these resources.[166] Energy transition policy is heterogenous at the state level, and states in the region have pursued efforts to protect coal assets rather than help communities transition from coal.[155,167,168] In response to the demand for oil and gas, communities engaged in oil and natural gas extraction in the Northern Great Plains region grew faster than the regional average (14% compared to 6%),[8] and oil and natural gas extraction is expected to remain at or near current levels through 2030.[169] Renewable energy production is on the rise in the Northern Great Plains, with the region supplying 12% of the total US electricity generation from wind, biomass, and solar sources.[163,170] Wind electricity generation tripled in the region between 2011 and 2021 and was often co-located alongside row crop agriculture (Figure 25.8).[159,170] A growing number of Tribal entities are leading the Nation's renewable energy transition by installing renewable energy projects, including the Pine Ridge Indian Reservation in South Dakota (solar), the Oceti Sakowin Power Authority (wind), and the Confederated Salish and Kootenai Tribes in Montana (hydroelectric).[171,172,173] The Inflation Reduction Act of 2022 (IRA) is expected to accelerate deployment of renewable energy sources,[169] and the region may benefit from investments in hydrogen hubs; carbon capture, utilization, and storage; and advanced nuclear reactors (Ch. 5).[174] Without the IRA and other climate mitigation policies, additional energy produced by new renewable energy sources is expected to only meet the increased energy demand by 2050 rather than replace the current usage levels of petroleum and natural gas.[163]

## *Community Infrastructure and Quality of Life*

Tribal lands, governments, and peoples are integral to the energy, agriculture, and recreation sectors. Immigrant populations are tied to agriculture in the region through their role in meatpacking, dairy, and other key industries. These communities face social vulnerability to harm from environmental hazards (Figure 25.8d). Communities across the region have experienced damages to infrastructure, businesses, homes, and livelihoods due to extreme events, including drought (2017, 2021), hailstorms (2018), flooding (2019, 2022), and wildfire (2021).[41] For example, after the 2019 Nebraska floods, community-level impacts included damage to homes, lack of water and sanitation services, and increased levels of anxiety and stress.[175] The effect of floods on the Santee Sioux Tribe included interruptions to power and drinking water supplies, wastewater backups, and destruction of many bridges and buildings (Figure 25.8d, point A).[176]

Future extreme events will disproportionately affect communities in the Northern Great Plains region that have greater exposure and sensitivity to hazards and fewer resources to prepare, respond, and adapt compared to larger cities.[12] For example, two storms damaged nearly 600 homes on the Pine Ridge Indian Reservation in July 2018, half of which were not repaired one year later (Figure 25.8d, point B). In 2019, the region experienced widespread flooding and damaged roads,[177] stranding many residents without access to basic needs. Many communities were disconnected from major highways, and infrastructure repairs are still underway. In drought years, communities dependent on surface water, such as those across the Crow Reservation, are seeing water resources and adaptation options become increasingly scarce (Figure 25.8d, point C).[166]

The lack of resilient infrastructure combined with regional climate impacts has created extreme water insecurity for Indigenous communities.[178] In the region, $159 million (in 2022 dollars) would be needed to bring either sewer or water access to 175 Tribal communities. Further, there are upwards of 18,000 homes within the region in need of sanitation (water and sewer) repair.[179]

Finally, regional residents living in housing or locations that are vulnerable face potential harms due to climate change. States in the region have a higher percentage of mobile and manufactured homes (e.g., 12.3% in Wyoming and 10.4% in Montana) compared to the US average (5.5%).[8] Mobile and manufactured homes are physically more vulnerable to extreme heat, flooding, and wildfires, exacerbating impacts from disasters.[180] Homes in floodplains are disproportionately occupied by renters and non-White populations. In Nebraska, Hispanic residents are overrepresented in floodplain areas (18% compared to 9% of residents in non-floodplain areas),[181] which resulted in disproportionate impacts to their housing security during the 2019 flooding in areas like Fremont and Grand Island, Nebraska (Figure 25.8d, points D and E).

## Key Message 25.4

## Climate Response Involves Navigating Complex Trade-Offs and Tensions

Climate change is creating new, and exacerbating existing, tensions and trade-offs between land use, water availability, ecosystem services, and other considerations in the region, leading to decisions that are expected to benefit some and set back others (*very high confidence*). Decision-makers are navigating a complicated landscape of shifting demographics, policy and regulatory tensions, and barriers to action (*high confidence*). Changes in temperature and precipitation averages, extremes, and seasonality will alter the productivity of working lands, resulting in land-use shifts to alternative crops or conversion to grasslands (*likely, medium confidence*). Shifts in energy demand, production, and policy will change land-use needs for energy infrastructure (*likely, medium confidence*).

Communities across the Northern Great Plains region experience complex tensions and trade-offs between land use, water availability, ecosystem services, and other factors, all exacerbated by the impacts of climate change. For example, higher temperatures and a longer growing season make the region attractive for climate-driven human migration[9] and increased forage production,[1] which in turn increase the demand for water resources. However, shifts in precipitation and reductions in snowpack will alter the quantity and timing of available water.[60] These tensions culminate in difficult decisions about how best to manage water quantity and quality and balance trade-offs between consumptive and ecological uses. Chapter 18 highlights frameworks for understanding complex systems, cascading effects, and decision-making under uncertainty.

### *Tensions: Navigating Barriers to Mitigation and Adaptation*

Decision-makers are increasingly aware of current and projected climate change impacts, and communities are trying to adapt and mitigate. However, there are cultural, structural, and institutional barriers that prevent effective action in the Northern Great Plains region. States within the region currently rely on fossil fuel economies, creating resistance to energy transition and economic diversification.[155,156,182] For example, Wyoming has passed legislation designed to hamper the retirement of coal plants and to ensure a continued market for coal generation.[167] Other examples of barriers include less research funding than other regions;[183] lowered capacity to adapt (Box 25.1); varying perceptions of climate change;[184] and a confusing, and occasionally contradictory, set of water regulations and rights around surface water storage (e.g., implementation of artificial beaver dams to retain water on the landscape).[185,186] These factors limit transition planning and undermine community-level resilience.[168]

Integration of climate change into K–12 science education standards in the Northern Great Plains region varies greatly, with several states in the region failing to link human activities to climate change.[187] Acceptance of the human link to climate change is lower than the national average among adults in the

Northern Great Plains region, with particularly low acceptance among agricultural producers and agricultural interest groups.[188,189] This lack of acceptance highlights barriers to collective understanding and climate change response in the region and is matched by a stronger evidence base for actions that emphasize adaptation and resilience rather than mitigation (KM 25.5).

The employment, income, and public revenue impacts of the transition away from fossil fuels will vary by geography.[190,191] Declines in coal demand have, and will continue to have, negative effects on rural coal-dependent states and communities, such as Rosebud and Big Horn Counties in Montana.[155,156,192] The public revenue gains from renewable energy could be substantial but uneven, reflecting both the impact of facility siting on regional economic opportunity and the impacts of tax policy on the ability of state and local governments to capture and retain tax revenue.[155,193,194] Specifically, state taxation and expenditure limits preempt governments from generating revenue from diversified economic growth,[195] including from renewable energy, and tax incentives designed to lower costs for renewable energy projects can undermine the revenue benefits of an energy transition.[196] Tribal communities in this region also face barriers to developing and benefiting from renewable energy on Tribal lands, including a dependence on federal agencies for permitting, limited access to private finance, and an inability to access federal incentives, which makes private investment on Tribal lands less attractive.[197,198] Decision-makers and communities in the region have increased efforts to incorporate multiple values and ways of knowing (e.g., Indigenous Knowledge, local experience, and empirical science) into planning and action (KM 25.5).

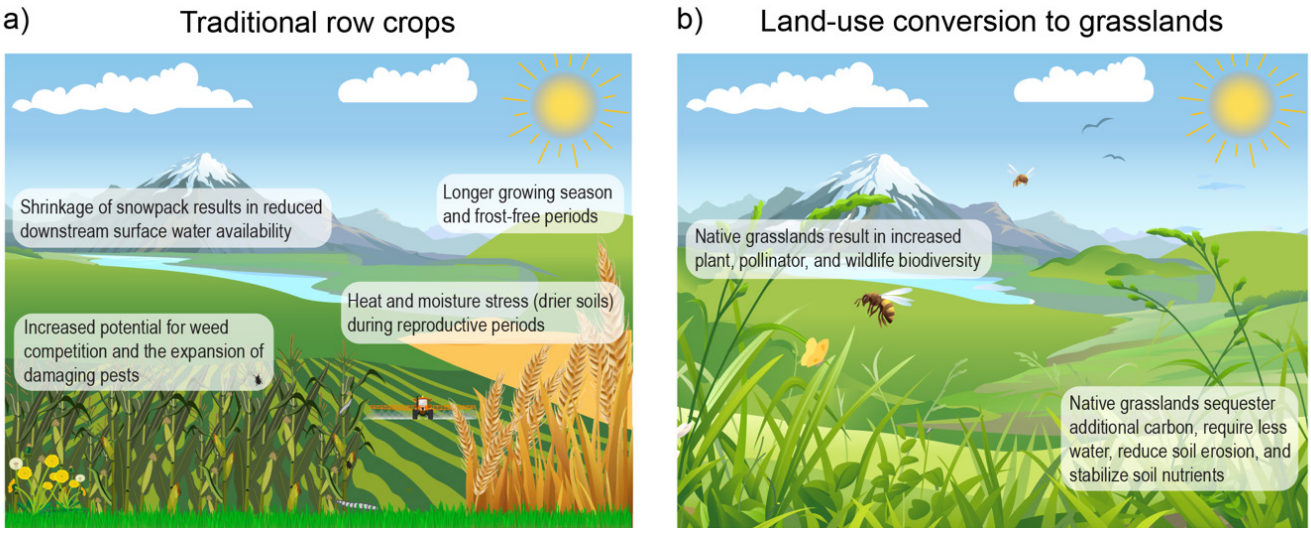
## Box 25.1. Rural Capacity and Funding

With $1.28 trillion (in 2022 dollars) in funding, the Infrastructure Investment and Jobs Act is one of the largest investments in infrastructure, community resilience, and climate response in US history.[199] To successfully plan for and finance climate mitigation and adaptation projects, communities require capacity, staffing, resources, and expertise to apply for funding; fulfill reporting requirements; and design, build, and maintain infrastructure projects over the long term.[200] States where capacity to support these efforts is limited receive fewer federal resilience grants, and federal programs that create a need for capacity to apply for and manage grants can erode local capacity that could be utilized for other purposes, thereby discouraging participation.[201] Federal funding agencies can utilize maps of capacity at the local-government level to identify and support communities that lack staff and expertise to compete for climate mitigation and adaptation, community resilience, and economic development resources. Montana, Nebraska, North Dakota, and South Dakota rank among the 10 states where the greatest share of communities have a Rural Capacity Index lower than the national medium.[202] Key Message 20.3 further describes the role of governance and policy in risk, adaptation, and equity.

## *Trade-Offs: Land-Use Conversion*

To counterbalance the potentially negative effects of a warmer future climate and drier soils, a shift to more water-conservative and nutrient-retentive land cover may be needed, such as from row crops to grassland (Figure 25.9). This would enhance ecosystem services such as wildlife, flood retention, nutrient stabilization, and carbon sequestration.[203,204] While this would increase resilience, it would also require many social and infrastructure adjustments and investments, including identifying seed sources for native species. Crops and services produced would shift from grain to forage, animal products, native plant seed, biofuel from grass, increased hunting on private land, and carbon credits. This would disadvantage companies that currently serve the high-input needs of conventional farmers but result in smaller loans for grassland producers due to less costly equipment, smaller seed purchases, and less grain shipped overseas.

## Land-Use Conversion as a Strategy for Climate Adaptation




**Land-use conversion offers one strategy for adapting to climate change.**

**Figure 25.9.** Climate stressors interact with regional land-use decisions in complex ways. Recent and historical land-use decisions (**left**) are altering the productivity of working lands. Potential alternative land-use decisions (**right**) have the potential to increase resilience against climate change. By converting agriculture to grassland in areas that will become marginal for production, landowners and resource managers can conserve water and enhance ecosystem services. Figure credit: USGS.

Transitioning away from fossil fuel energy systems is expected to result in the abandonment or reduction of fossil fuel energy infrastructure (e.g., pump jacks, well bores), siting of new wind energy generation (e.g., wind turbines), construction of linear transmission $CO_2$ pipelines, and continued land conversion to biofuels.[165,205] Because renewable energy sources are expected to require larger land areas (3 to 25 times larger) to produce similar amounts of energy as nonrenewables,[206,207] a trade-off exists between providing energy and conserving the few remaining intact grassland tracts in the world.[208,209] Fragmentation of these tracts by energy infrastructure involved in harvesting and transmitting energy can reduce wildlife populations and provide conduits for invasive species.[159] Siting of energy infrastructure on areas already disturbed by row-crop agriculture or other activities may help prevent further fragmentation in some areas but may not be a possibility in the more intact grasslands of the Northern Great Plains that are relatively undisturbed.[159,209,210] Water-use trade-offs are another concern with energy development. Water law can influence the ability of industry to access water rights in low-flow years.[211] For instance, state and federal environmental policy may limit options to generate power from fossil fuel plants that require water for cooling during low-water years, which are projected to become more frequent (KM 25.1). Additionally, legal challenges related to water quantity and quality for endangered fish set up trade-offs between energy, wildlife, and recreation.[212,213]

Another adaptation action, piloted locally on less productive farmland with promising regional mitigation potential, is planting low-input, productive tall grasses, such as switchgrass, as dedicated biofuel energy crops (Figure 25.10).[214] This approach sequesters carbon from the atmosphere,[215,216] and marketing this alternative crop for forage, seed, or biofuels could generate income equal to or exceeding current income.[217] Switchgrass is a native plant that requires little fertilization and is especially resilient to drought. Biofuel feedstocks could be burned to generate electricity or converted to ethanol or bio-oil, syngas, and biochar. Planting grasses would store more carbon in the soil, require fewer inputs of fossil fuel compared to the annual planting of conventional crops, and improve other components of soil health.[218] However, large-scale land-use conversion to biofuel energy crops could disrupt food production processes, reduce biodiversity, and drive water competition.[219]

### Marginal Farmland Planted to Switchgrass

**Conversion of cropland to production of biofuels such as switchgrass is being piloted in the region as a climate adaptation action.**

**Figure 25.10.** Switchgrass is a highly productive native prairie perennial that is the most promising species for future commercial growth as biofuel (for use as liquid transportation fuels and in electricity production). Photo was taken in 2021 at an experimental farm near South Shore, South Dakota, following two summers of drought, when production of switchgrass hay was 5 tons per acre and was more profitable than the production of corn. Photo credit: ©Arvid Boe, South Dakota State University.

## Key Message 25.5

## Communities Are Building the Capacity to Adapt and Transform

Adaptation is underway in the Northern Great Plains to address the effects of climate change. Agricultural communities are shifting toward climate adaptation measures such as innovative soil practices, new drought-management tools, and water-use partnerships (*medium confidence*). Several Tribal Nations are leading efforts to incorporate Traditional Knowledge and governance into their adaptation plans (*high confidence*). Resource managers are increasingly relying on tools such as scenario planning to improve the adaptive capacity of natural ecosystems (*medium confidence*).

Effective adaptation accounts for climate change uncertainty as well as the complex interactions and trade-offs within and between ecological and social systems (Ch. 31).[220,221] The failure to carefully navigate the full suite of adaptation options and the consequences of those options can result in maladaptation—increased vulnerability to climate change due to poor or misguided action (Box 25.2)[222] or inequitable distribution of outcomes. Despite these challenges and risks, climate adaptation planning also presents opportunities to build collaborative partnerships and steward ecosystems.[223] The communities, economic sectors, and natural resource practitioners in this region are advancing adaptation solutions (Box 25.3).

## Box 25.2. Prairie Pothole Wetlands and Climate Adaptation Challenges

In the eastern Prairie Pothole Region of Minnesota, North Dakota, South Dakota, and Iowa, an increase in rainfall in the spring season has exacerbated problems with excess shallow groundwater in farm fields. Farmers have responded by draining this water with perforated plastic pipes (known as tiles; Figure 25.11)[224,225] buried at the rooting depth of mature corn plants, a practice that improves crop yield.[226] Tiling has increased rapidly in eastern North and South Dakota, particularly in the Red River valley.[227,228,229,230] To date, approximately half of the wetlands in the Northern Great Plains have been drained, disrupting their ecosystem services, such as flood protection, carbon sequestration, and forage and water for livestock.[231,232] Drainage transforms the hydrology of downslope ecosystems, contributing to the widening and sedimentation of rivers,[224,233,234,235] and promotes toxic algal blooms in aquatic systems through transport of nutrients (especially phosphorus and nitrate).[236,237] Additionally, improper placement of tiles may drain water from nearby wetlands.[226] Adaptation actions to regain wetland benefits and respond to climate change include restoring grassland and drained wetlands, redoubling the protection of wetlands with easements, revising vegetation management of wetland watersheds, and discouraging tile drainage in farm fields with wetlands present.[238,239,240,241]

### Pattern Field Tiling

**Draining agricultural fields through tiling improves crop yields but can harm ecosystems.**

**Figure 25.11.** Pattern field tiling in the Prairie Pothole Region is designed to drain low, wet ground to provide soil space for roots of crops, which can increase yields. Tiling can inadvertently drain wetlands if placed too close to or below the elevation of the wetland bottom. Plastic pipe is buried at each black line visible in the photograph. Photo credit: USFWS.

## Box 25.3. Climate Adaptation Successes

Climate adaptation happening in the Northern Great Plains region includes farmers in Nebraska testing new methods to improve soil structure and hydrologic function, Indigenous communities returning buffalo to their lands, ranchers returning less productive farmland to grassland for forage production, and local communities responding to flooding and working to improve flood readiness.

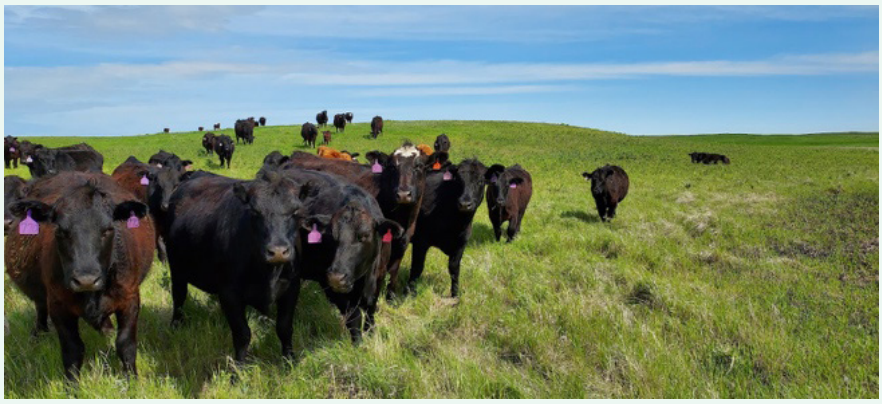
### Adaptation Through Soil Health

Restoring soil structure and hydrologic function is a critical adaptation strategy in the Northern Great Plains region. In Nebraska, the Natural Resources Conservation Service has used federal conservation program dollars to support farmers testing soil health management practices, such as incorporating cover crops into annual crop rotations. Partnerships that leverage on-farm trials with outreach and research contribute to growing both the knowledge base and the execution of crop and livestock management practices that support improved soil function. Benefits include water-related outcomes such as increased infiltration and reduced runoff. Photo credit: USDA

### Bringing Back the Buffalo

Bringing back the buffalo has been a regional resilience-building strategy for ranchers, Tribal Nations, and others who understand the role it plays in the ecosystem. The buffalo has deep cultural and spiritual significance for Tribal Nations in the region and beyond. The Tanka Fund has been pivotal in this regional effort by connecting ranchers to technical support and resources to increase herd sizes. Similarly, the InterTribal Buffalo Council helps Tribal Nations develop and maintain their own herds. These two entities connect resources to people and Tribal Nations looking to restore the buffalo as the keystone species of grassland ecosystems. Photo credit: NPS

### Restoring Native Perennial Land Cover



As climate changes, it may be beneficial to return less productive cropland to native perennial cover that can provide multiple ecosystem services, including climate mitigation through carbon storage, pollinator benefits, and forage production for livestock. Audubon Great Plains, in partnership with government organizations and other nonprofits, is leading a new Conservation Forage Program in North Dakota to help producers achieve this shift in land use to benefit both producer operations and natural resources. Programs such as these that provide technical and financial assistance to producers while also helping to establish the necessary infrastructure for grazing (e.g., fencing, water access) and allow livestock use after vegetation establishment will allow farmers and ranchers flexibility in their operations. Photo credit: ©Reese Lausen

### Responding to Increases in River Flooding

Flooding along major rivers is an increasing challenge for rural and Indigenous communities in this region. In March 2019, a 64-unit Tribal housing community with more than 300 Yankton Sioux members on the edge of the Lake Andes National Wildlife Refuge was inundated with floodwaters and cut off from the town of Lake Andes. Subsequent heavy rain events flooded basements and made the road inaccessible until the water over the highway froze in December. On August 12, 2019, the Tribe released a statement: "Our community is literally drowning."[242] The White Swan Recovery Group was created to provide resources for impacted community members and advocate for long-term solutions. The group received training to provide local lead and mold remediation and housing repairs. They continue to explore long-term solutions as the area is subject to frequent flooding; these efforts include advocacy to elevate the highway to protect housing, as well as conversations regarding relocating the community. Photo credit: Marcie Hebert, USFWS

## Adaptations in Agriculture

The agricultural community in the Northern Great Plains region is developing innovative climate adaptation solutions to support livelihoods in the region (e.g., Johnson and Knight 2022[243]), many of which also support mitigation by sequestering carbon (Ch. 11). Stakeholders recognize that soil improvements increase flood and drought resilience.[244] Growing evidence from working farms and ranches in the region demonstrates how diversification strategies—such as reduced soil disturbance, increased crop residue, plant cover, and livestock and crop diversity (sometimes referred to as soil health or regenerative practices)—improve soil properties and processes, including water-holding capacity and infiltration, and provide many potential public and private co-benefits, including carbon sequestration.[245,246,247] These properties and processes produce enhanced carbon and nitrogen cycling and soil structure,[240] increased soil microbial communities, and lower pest communities while reducing nutrient inputs and leading to greater yields and profitability.[248,249,250,251,252] There is strong demand for, and proven efficacy around, producer knowledge networks to support transitioning to soil health practices.[253,254] Additionally, reintegrating row crop and livestock production systems could diversify income, increase operation resilience,[246] and restore ecosystem services, including sequestering more carbon in soil; retaining nutrients, especially nitrate; and supporting biodiversity.[108,217,255]

In arid parts of the region, adaptive solutions for irrigated agriculture will be critical. The majority of the region's states assign water rights based on prior appropriation, under which the first person to put water to beneficial use has the right to continue to use that water as long as the water is being used for the same beneficial use. This can slow the ability to acquire new water rights that may be necessary to address climate impacts.[256] The Upper Colorado River Commission (UCRC), as part of the 2019 Drought Contingency Plan,[25] is investigating the feasibility of implementing a demand-management program in the Upper Division states of the basin, including Wyoming. Under this program, water users would be compensated for voluntarily reducing consumptive uses. The conserved or imported water would be stored in federal reservoirs and released when needed to ensure compact compliance under a decision of the UCRC. On a smaller scale, many watershed and irrigation groups are investigating collaborative and shared water management strategies to manage scarce water resources to meet agricultural and ecological water needs, including the Brush Creek Irrigation District[257] and the Popo Agie Watershed Healthy Rivers Initiative[258] in Wyoming, as well as some Montana Tribes.[259] Instead of directly following the prior appropriation doctrines, different approaches to collaboratively manage water resources to meet agriculture and instream needs are being implemented. All of these efforts include and rely on improved hydrologic monitoring and data collection, as well as strong communication and buy-in from stakeholders.

Ranchers are also exploring adaptation strategies that increase livestock production by adjusting range management for a warmer climate.[260] One strategy to improve ranch resilience is through the use of drought planning.[261,262] Drought plans focus on identifying critical time periods for monitoring conditions and making decisions.[263] A planned drought response may involve adjusting the number of cattle, the season of grazing, the length of grazing time in pastures based on precipitation and vegetation growth,[264] or holistic planned grazing strategies that manage for ecosystem health by adapting to changing conditions.[265] A 2017 study found that nearly 60% of ranchers in the region had some type of drought contingency plan;[261] however, adoption of weather and climate data into management decisions has been slow.[136,266] The development of new grassland productivity forecasts may increase adoption by translating climate outlooks into usable information for ranchers.[267] Unique multistakeholder groups are also exploring collaborative adaptive management to understand and reconcile stakeholder experiences and ways of knowing about complex rangeland systems on public lands.[264]

## Adaptation to Flooding

In response to significant flooding in 2011 and 2019 in the upper Missouri River basin (UMRB), improved monitoring was implemented to inform water management decisions. Frozen and saturated soil and significant snowpack in the UMRB were major contributors to flooding in those two years. Additionally, the drought west of the Missouri River in 2016–2017 highlighted the problem of sparse soil moisture data inhibiting accurate drought monitoring. As a result, the US Army Corps of Engineers, in collaboration with the state climate offices, is establishing a soil moisture and snowpack monitoring network.[268,269] A total of 529 stations are scheduled for installation between 2021 and 2027 on a 25-square-mile grid at elevations below 5,500 feet. The data from these stations, which include multiple soil moisture and temperature depths, as well as snow depths, will be directly available to NOAA to track and forecast flooding, drought, and other climatic and weather events.

With increased spring precipitation across much of the region, rural and Indigenous communities are adapting to more frequent flooding. Adaptation responses range from individual-scale approaches, such as elevating homes, to policy changes, including changing building codes and zoning regulations. Nebraska's unique river-basin Natural Resources District structure has enabled watershed-scale approaches that bring together multiple jurisdictions and stakeholders to decrease flood risk.[270] More drastic responses considered by some communities include relocating altogether. One increasingly successful adaptation strategy for responding to flood and natural disasters is the grassroots formation of local groups and coalitions to assist communities with disaster recovery and long-term adaptation (e.g., Sioux Empire Community Organizations Active in Disaster in South Dakota, Midwest Housing Resource Network in Nebraska). These groups are a mechanism for local communities to come together in mutual aid to plan for and support each other in response to flooding.

## Adaptations in Indigenous Communities

Indigenous Peoples have called the Northern Great Plains region home for centuries, and today several regional Tribal Nations are leading the way in climate adaptation and implementation.[271,272,273] Several other Tribal Nations are leading the effort in water resilience and proactively addressing drought.[274,275,276,277] Indigenous approaches to adaptation combine traditional and contemporary management practices often grounded in spirituality and cultural traditions.[278] The key issues for Tribal climate adaptation in the region are capacity, sustainability, and sovereignty.[197]

The Rosebud Sioux Tribe has several initiatives in progress to build resilience to climate change.[279,280] The Sicangu Climate Crisis Working Group developed a Tribal climate adaptation plan that covers 20 Tribal communities across more than a million acres of Tribal land. The plan incorporates Lakota philosophy and Traditional Knowledge, including historical migrations, astronomy, origin stories, and the Tribes' special relationship with the buffalo. The plan prioritizes data sovereignty, interdepartmental collaboration, and directly supporting Tribal households to prepare for the impacts of climate change.[273] Additionally, the Rosebud Sioux Tribal Water Department has developed a drought adaptation plan and extensive real-time monitoring that enables the management of stream flow and groundwater sources, including the Ogallala Aquifer.[276] One of the major challenges has been the enforcement of the Rosebud water code to address neighboring farmers pumping Tribal-managed groundwater. However, with the removal of the moratorium on Tribal water codes, the Rosebud Sioux Tribe may now have the ability to manage its water as a sovereign nation.[281]

In 2018, the Blackfeet Nation completed a climate adaptation plan, which includes all of the natural resource departments across the Tribal government.[271] This inclusive approach takes more time and coordination but also creates collaborative opportunities by breaking down silos, minimizing redundancy, and maximizing scarce resources. For many Tribal Nations, sustainability is a key issue. This was especially true during

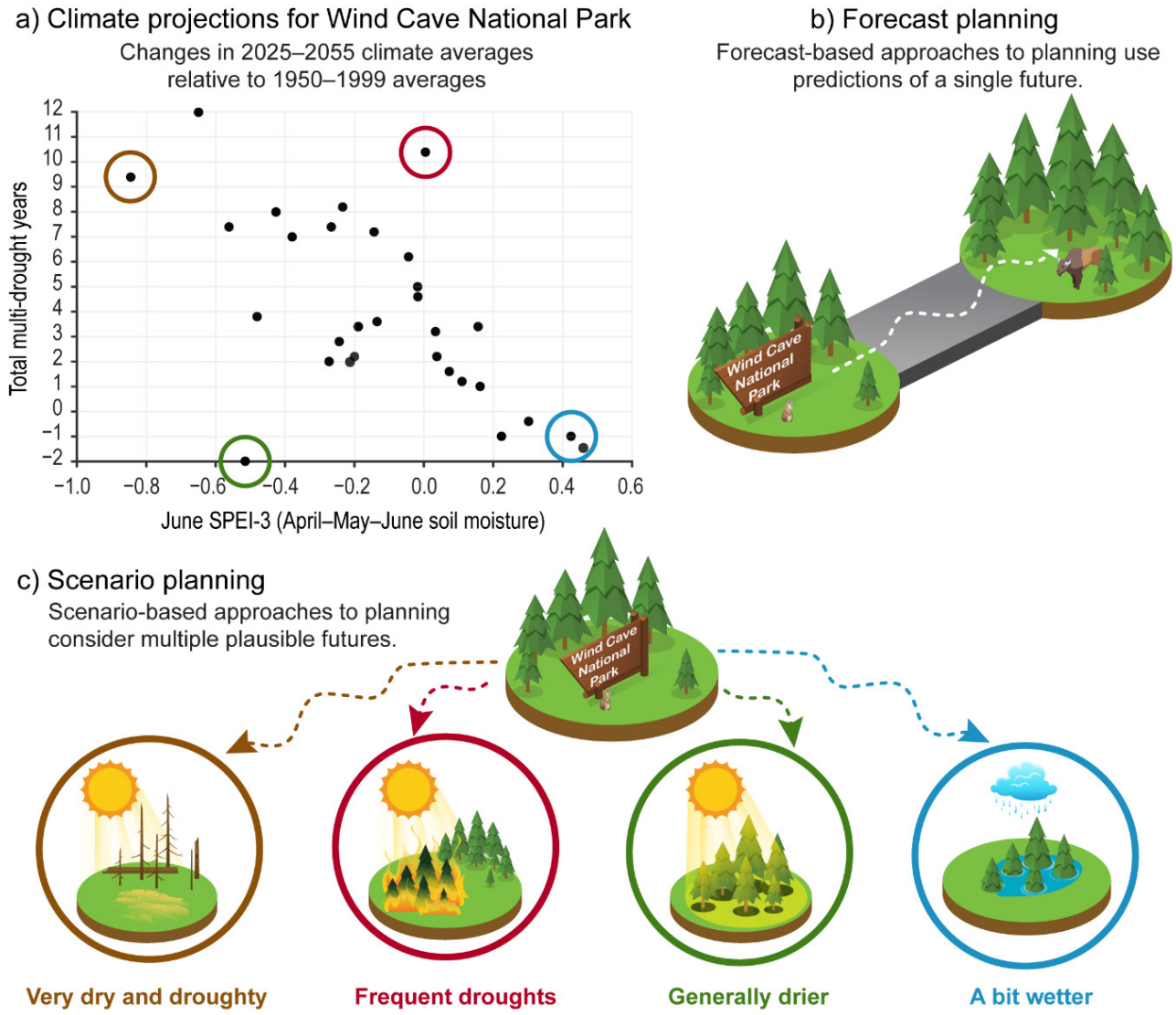
the COVID-19 pandemic and continues to be the reality in rural agricultural regions with smaller tax bases and higher turnover rates in staffing. Implementation includes the Ksik Stakii Project, which aims to protect beaver, restore rivers, and increase natural water storage to reduce vulnerability to drought and flooding.[271,282] A notable capacity-building strategy at Blackfeet is for Tribal resource departments to partner directly with Blackfeet Community College students on research projects. This type of a partnership is particularly important in the Northern Great Plains region, which has the highest concentration of Tribal colleges in the country.

## *Public Land Adaptation*

The National Park Service (NPS) and partners have adapted scenario-based planning to help natural and cultural resource managers and others work with uncertainty and address the ways change might plausibly occur (Ch. 8).[283,284] Adaptation action on public lands in this region is challenged not only by the region's inherent climatic variability but also by the uncertainty in how resources, lifeways, or livelihoods might be affected by climate change and which adaptation responses might be effective (Figure 25.12).

Adaptation of scenario-based planning for public resource stewardship has focused on NPS units within the region—including Knife River Indian Villages National Historic Site, Badlands National Park, Wind Cave National Park, and Devils Tower National Monument.[283,285,286,287,288,289,290,291] This work has increased scenario plausibility and relevance and improved facilitation and efficiency of climate adaptation decision-making.[283] It has also clarified the importance of distinguishing climate futures (i.e., climate scenarios) from climate-resource scenarios (i.e., scenarios of both changes in climate and associated changes in resource condition).[289,292] Importantly, this work has created a model to support climate adaptation for natural resource decision-making in the face of climate uncertainty.

## Adaptation Planning




**Scenario-based planning accounts for uncertainty by considering a range of ways in which change might occur.**

**Figure 25.12.** Forecast-based planning uses predictions of a single future (**b**), whereas scenario-based planning works with a set of plausible futures that capture a broad range of potential future conditions, providing a framework to support decisions under conditions that are uncertain and uncontrollable. Scenario-based planning at Wind Cave National Park identified four potential outcomes (**a**, **c**) for grassland and pine forest vegetation, surface water availability, and American bison (*Bison bison*) and prairie dog colonies under different climate futures—very dry and droughty (brown), frequent droughts (red), generally drier (green), and a bit wetter (blue)—all of which have different management implications for the natural and cultural resources in the park. Each dot in the graph represents a climate projection, and the set of four circled projections collectively encompasses most of the range of ways in which drought and springtime moisture levels could change by midcentury. SPEI—the Standardized Precipitation–Evaporation Index—is a multi-scalar drought index, based on precipitation and potential evapotranspiration, that is used to identify wet and dry periods in a given location.[293] A zero value indicates average moisture balance, positive values signify above-average wetness, and negative values represent drier-than-average conditions. SPEI-3 is a three-monthly SPEI calculation, and this figure shows values for April–June. Adapted from Schuurman et al. 2022[294] and Runyon et al. 2021.[289]

## *Rural Community Adaptation*

Rural communities have two key needs to foster climate adaptation (KM 11.3). The first is economic diversification to create more resilient economies (e.g., broadband connectivity, restoration activities that create jobs and restore ecological function, and conservation that improves access and opportunity in recreation-based economies). The second is the need for a new social contract around resource extraction, especially for communities that will remain rural, isolated, and resource-dependent.[295] Major investments in community services, infrastructure, and economic development led by rural communities require long-term and sustainable funding to build capacity and resilience (Box 25.1).[194,200] Barriers to building adaptive capacity include a lack of coordinated federal assistance programs.[296] The region also has the potential for population growth in communities currently facing out-migration driven by favorable changes in climate coupled with a robust recreation economy, particularly in the intermountain West.[297,298]

# Traceable Accounts

## *Process Description*

The chapter lead authors were identified in the summer of 2021. This team compiled a list of nominated and Fourth National Climate Assessment (NCA4) authors as a pool of possible contributors. Additions to this list came from professional networks, research into priority departments at key regional institutions, and searches on several databases of experts from historically marginalized populations. The lead authors defined potential themes for the region based on team expertise and a review of literature published since the release of NCA4 and then narrowed the list of potential authors based on their ability to address these themes and a desire for diversity.

Candidates were selected based on a mix of expertise, regional distribution, career stage, age, gender, sector, discipline, and race and ethnicity. After preliminary research on potential contributors, introductory conversations were pursued to gauge interest and answer questions. The majority of the chapter team was recruited in September and October 2021, although as gaps were identified, other authors were added. Weekly all-author meetings started in September 2021 to craft the Zero Order Draft, with subgroup meetings held when needed to work out details. Once key topics were identified in December 2021, authors were divided into Key Message teams, based on interest and relevant knowledge. Virtual all-author meetings continued weekly, with Key Message teams meeting approximately every other week and more frequently before submitting the Zero Order Draft.

Key topics were identified through discussion, relevant literature, and knowledge of the region. Authors held two virtual engagement meetings, one during the day and one in the evening, to provide options for participants. Engagement events were promoted by the US Global Change Research Program through author networks, on social media, and with personal invitations to individuals whose voices the author team wanted to be represented. Feedback from engagement aligned well with the draft structure, but some of the emphases were adjusted based on stakeholder feedback. The author team incorporated inputs received in a public call for the technical material and relevant scientific publications and added several key technical contributors to bring other types of knowledge (e.g., Indigenous and experiential) that would provide a more complete assessment. Key Message teams discussed and came to consensus about Key Messages proposed in the First Order Draft and revised and came to consensus on Key Messages for the Second and Third Order Drafts. Key Messages were further iterated in the Fourth and Fifth Order Drafts to respond to comments from the public, National Academies, and agency technical review.

## Key Message 25.1

## Climate Change Is Compounding the Impacts of Extreme Events

### Description of Evidence Base

The role of climate variability in the region has been well established.[39,42,299] The added effect of climate change is still emerging. NOAA State Climate Summaries document long-term increases in temperature in the region and varying changes in precipitation across the region.[14,15,16,17,18] Recent USGS trend and attribution efforts reflect the trends in flooding presented here, and the majority of attributions for those changes are related to changes in precipitation, with some also related to changes in temperature.[43]

The upper Missouri River basin combines the varying effects of east–west and north–south gradients in precipitation and temperature, respectively, for the Northern Great Plains. However, the Key Message team

wants to acknowledge that the Northern Great Plains region also includes parts of the Columbia, Colorado, Souris, Red, and Minnesota River basins.

Multiple independent scientific assessments and analyses of climate change effects on drought occurrence in the region are reaching similar conclusions across multiple climate change scenarios.[22,26,45,48,51] The study showing increased wildfire activity in the Northern Great Plains is based on satellite data, which adds credibility, because the use of the same methodology to assess wildfire across the region eliminates discrepancies caused by differences in how local governments record wildfire occurrence.[57]

## Major Uncertainties and Research Gaps

Given the high degree of natural climate variability in the region, predicting future hydroclimatic and ecological conditions at specific locations is a major challenge. Climate change predictions of increased drought occurrence vary spatially and temporally. Complex interactions among temperature, precipitation, evapotranspiration, and moisture storage also create uncertainty for future conditions and agricultural production in this region (KM 3.4). As many of the projections of soil moisture predict close to no net change and the region already has a low effective precipitation that has high interannual variability, projected changes in soil moisture vacillate between overall net positive and negative changes.[47,48,49] Better understanding of how climate change affects soil moisture will require a greater assessment of the variability in soil moisture among global climate models and the incorporation of other factors such as soil type and plant species–specific responses at the local scale.[117,118]

Lack of long-term observations for small-scale and rare hail events and shortcomings in high-resolution models create uncertainty for predicting future events in specific areas,[28,29] so the models rely on trends in favorable hail environments.[30,31,32,33,34,35,300] Projections of severe convection in current research have largely focused on a very high scenario (RCP8.5).

Although drought frequency and severity are expected to increase, changes in multiyear drought occurrence due to climate change are relatively unknown.[45,52,53] Research on wildfires in the region has not addressed how human presence has influenced wildfire activity in the grasslands but has covered it in the forests.[58]

## Description of Confidence and Likelihood

The coauthors of this section discussed the initial levels of confidence and likelihood, weighing the literature, observational data, and collective subject-matter expertise. The authors assigned a *likely* estimate with *high confidence* for an increase in severe droughts because of the pervasive evidence that increasing summer temperatures will increase evaporative demand, while changes in precipitation patterns lean toward increasingly dry summers. The authors assigned a *medium* confidence and no likelihood estimate for increasing hail frequency and size because the literature is still emergent and precludes a likelihood estimate but does present evidence that suggest increasing hail frequency and size in the High Plains area under at least some climate change scenarios. The authors assigned a *very likely* estimate with *high confidence* for changes in flood potential because research and observations strongly support both an increase of snowmelt runoff and flood potential in the eastern half of this region and respective decreases in the west. NOAA State Climate Summaries cited predict increases in extreme precipitation, which are expected to increase flood risk, even in areas with declines in overall precipitation. The authors assigned a *likely* estimate with *high confidence* for increased wildfire risk because the increase in evaporative demand and precipitation variability that favors drought also favors increased numbers of wildfires. Research indicating shorter duration of snowpack coverage also favors longer wildfire seasons. The authors assigned a *very likely* estimate with *very high confidence* for increases in evapotranspiration because multiple sources and subject-matter experts agree that the increasing warm-season temperatures will increase evaporative demand. The authors assigned a *very likely* estimate with *high confidence* for greater precipitation variability

because of the depth of both observational and model-based studies and consensus among subject-matter experts for current and future trends toward increased variability.

## Key Message 25.2

## Human and Ecological Health Face Rising Threats from Climate-Related Hazards

### Description of Evidence Base

Climate trends from NOAA State Climate Summaries,[14,15,16,17,18] individual state-level climate assessments, USGS studies,[43] and demographic data from the 2020 US Census Bureau provided information to help characterize the region in terms of ecological conditions[99,100,101] and human populations.[61] CDC databases were also used extensively for health-related statistics. Multiple recent peer-reviewed studies of the impacts of specific aspects of climate change on human health were reviewed and included in the assessment. With relatively few region-specific studies of the health impacts of climate change, analyses based on areas with more concentrated populations provided valuable insights that are applicable to the Northern Great Plains. Several studies related to mental health have addressed the impacts on ranchers and farmers, rural residents, and Indigenous populations and are included in this assessment.[73,75,76] Many studies predict water quality changes in response to climate change; fewer studies have identified such changes.[90] Land-use change was predicted to be a larger driver of changes in water quality than climate change, and, along with management practices, land-use change appears to be the major driver in many cases;[90,91] however, the interaction of land use, management practices, and climate extremes is an important area for future research and potential harm reduction.[93,94,95]

### Major Uncertainties and Research Gaps

The complex interactions among climate-related indicators themselves, with even more variability contributed by the considerable east–west geographical expanse of the region, lead to notable uncertainties for future climate conditions and the interactions between those climate conditions and local populations. The overall low population and population density across the region make data collection relative to health-related impacts difficult, adding to even more uncertainty in projections for impacts on individuals or locales. Research gaps include limited studies relating to health impacts specific to the region. In addition to the demographic barriers noted above, many areas within the region have limited sensors for measuring local conditions related to air quality, temperature, water quality, and air and soil moisture. The paucity of sensors, most notable in nonurban areas of the region, for these conditions introduces uncertainty when focusing on specific locations. The need for location-specific data is particularly important when addressing adaptive measures, since some conditions, such as air quality and temperature, can vary dramatically within small geographical areas.

Climate impacts on the ecology of the Northern Great Plains are difficult to generalize because individual species are expected to respond very differently to changes in climate. While declines have been observed and are projected for some taxa,[104,106] there are knowledge gaps around what those impacts might be for many taxa, species, and culturally significant plants and animals. Climate impacts will interact with and are expected to compound many other anthropogenic stressors, such as invasive species and conversion of natural ecosystems to row crop agriculture, and it is unknown which taxa are most vulnerable to climate change and what the magnitude of these impacts could be.

While the authors understand water-quality and physical processes related to climate, many management activities designed to reduce nutrients are taking place on the landscape, along with changing agricul-

tural nutrient requirements. Therefore, it can be difficult to find the climate signal in trends related to surface water quality, apart from the signal related to other important factors, such as land use, agricultural practices, and wastewater treatment.[90,94] The problem of attribution is further confounded by the complex effects of reaction-transport lags between any climate or landscape-scale driver and detectable changes in nutrients in surface or groundwater.[90,91] Recent findings based on observational data[90,91] support past predictions that land-use changes would have comparable or greater effects on water quality than climate changes.

Climate change has long been hypothesized as a driver of harmful algal blooms. Warming water temperature, higher carbon dioxide levels, and increases in heavy precipitation can create preferential conditions for algae. Blue-green algae can thrive in warming, slow-moving water; high carbon dioxide levels can result in rapid algae growth; and heavy precipitation can result in more nutrient runoff.[96] Unfortunately, supporting these hypotheses with observations has been challenging because of gaps in monitoring, lack of long-term algae data, and changes in laboratory and remote-sensing methods.[97,98]

### Description of Confidence and Likelihood

Likelihood and confidence statements for climate change impacts on the health of residents of the region (*virtually certain*, *high confidence*) and on the region's ecology (*very likely*, *medium confidence*) are based on literature, some of which is cited in Key Message 25.2, observational data, and collective subject-matter expertise. The *very likely* rating for the region's ecology in both likelihood statements was based on the information that impacts are already being observed, and the *medium confidence* rating for both confidence statements was assigned because data or projections of impacts exist for some taxa but not all. Impacts to some aspects of the region's ecology are unclear or unknown. The research gaps and uncertainties listed in the preceding section limit the ability to project impacts for specific locations but do not lessen the confidence regarding current impacts on the various aspects of human health in the region as a whole, assertions strongly supported by an increasing number of studies (Ch. 15).[301] Levels of confidence and likelihood have been discussed in an ongoing fashion among the coauthors of the section, who weighed the overall literature and personal expertise to reach consensus for the stated levels.

## Key Message 25.3

## Resource- and Land-Based Livelihoods Are at Risk

### Description of Evidence Base

Multiple national government economic reports provide the background for population growth and the importance of the agricultural and energy sectors to livelihoods in the Northern Great Plains. The most recent comprehensive syntheses of crop and climate impacts,[3,114,119] the most recent publications focused on Indigenous communities,[126] and the most recent foundational publications on crop physiology impacts of climate change at a broader scale than the region[120] support the projected negative impacts that rising temperatures would have on crop and culturally significant plant yields and timing. The net effect of climate change on agricultural livelihoods is uncertain due to the unresolved interacting effects of temperature, soil moisture, and carbon dioxide levels, as well as the degree of climate adaptations that may occur.[120,122] Projected aboveground net primary productivity increases and effects of drought are well documented across multiple scientific papers,[129,130,131] with recent papers supporting older papers from the literature and reinforcing the expected outcomes. The current resilience of rangeland-based livelihoods[135,136] and their future challenges[137,138] are well documented and in agreement. Although extensive peer-reviewed literature does not exist for climate effects on tourism and recreation, a few peer-reviewed literature examples documented climate change impacts on water-based, hunting, winter, and sightseeing recre-

ational activities.[150,151,153] The scientific literature on projected changes in electricity use within the region in response to climate change is readily available and in agreement (Ch. 5),[157,158] but literature on energy resource and electricity demands on the region from outside the region is limited and lacks specificity.[155,159] Examples of increasing and shifting types of energy demands on the region are well documented in both peer-reviewed scientific literature as well as government reports,[163,165,169,170] but comprehensive literature reviews providing overviews of how all energy shifts are occurring in relation to one another and in response to climate change and climate change policy are lacking. Literature on the effects of current and projected energy demand and shifts among types of energy sources on the livelihoods within the region is less available, and information is gleaned from government reports.[8] The impact of climate extremes on energy infrastructure is general in nature (Ch. 5)[161] and does not cover climatic variability and extremes unique to the region for all the energy infrastructure types found in the region.[162] Peer-reviewed literature on climate change impacts to livelihoods in the region does not fully address recent extreme events, so agency reports (e.g., FEMA 2019[177]) and Tribal documents (e.g., Blackfeet Nation 2022[139]) are used to document examples of impacts. This is also the case with Tribal infrastructure, where critical information on infrastructure was pulled from Indian Health Service and Bureau of Indian Affairs reports. Impacts are also identified by a technical contributor (Cullen) who works directly with communities affected by disasters in the region.

## Major Uncertainties and Research Gaps

As stated in the text of the Key Message, the net effect of climate change on specific crop yields is uncertain, and multiple interacting effects would benefit from further study to fully grasp how climate change will comprehensively impact the agricultural industry, especially as it develops cultivars and management practices that adapt to the changing environment.

The net impact on forage quantity and quality in the region remains to be further explored. Productivity responses of Northern Great Plains rangelands to climate change have a degree of uncertainty, as the response of the vegetation to climate change may vary between the two dominant plant functional groups ($C_3$ and $C_4$). Scaling up the climate change responses of individual species and functional groups and how they contribute to larger ecosystem processes and properties, such as evapotranspiration or productivity, is important for improving the forecasting of climate change impacts to grasslands and shrublands in the region; this is a research gap. There is also uncertainty about how the negative impact of drought, which is expected to increase under climate change, will impact the expected positive gains on forage quantity and quality due to rising temperatures and elevated carbon dioxide.

Comprehensive studies of how climate change will affect tourism and recreation in the region are missing from the literature. Climate change impacts on tourism livelihoods are often limited to case studies and would benefit from more directed scientific study. Although some climate change models predict changes in insect outbreaks, which can lead to large impacts on recreational areas, correlations between outbreaks and climate change (e.g., mountain pine beetle) were not widespread, indicating a research gap in understanding all the interactions contributing to the relationship of observed outbreaks and climate change (e.g., Weed et al. 2015[152]).

Further studies detailing how increased national energy demand impacts regional energy harvest would provide a deeper understanding of the economic connections that in turn greatly affect regional communities. Strategic planning for the development of new oil and gas resources while transitioning to other energy resources in the region could benefit the grassland resource as a whole. Carbon capture, utilization, and storage (CCUS) in the region may play a role in mitigating US emissions. However, little carbon is currently being sequestered, and documentation of the costs and benefits for the region, as well as its many barriers and uncertainty, is a major research gap. It would be helpful to gather more information

on these topics before CCUS technology is deployed at scale in the region. Specific research examining how energy infrastructure in our region would respond to climate extremes is another research gap.

The effects of extreme events on agricultural, energy, and recreation-based livelihoods are often investigated more by the general media than by scientific studies and are therefore insufficiently covered in the research literature. This is also apparent when trying to evaluate the impact of climate change and climate extreme events on socially vulnerable communities. Peer-reviewed literature focused on climate change effects on rural and Indigenous communities in the region is a research gap.

### Description of Confidence and Likelihood

The coauthors of this section discussed the initial levels of confidence and likelihood, weighing the literature, observational data, and collective subject-matter expertise. The authors assigned a *likely* estimate with *medium confidence* for agriculture and recreation seeing some positive but primarily negative effects of changing temperature and precipitation regimes on livelihoods. The *medium confidence* level was assigned because regional-specific agricultural literature is limited and requires multiple sources to be pieced together to evaluate the likelihood and confidence of changes in agriculture, and because recreation and tourism literature was limited to case studies often focused on extreme climate events that could increase with climate change. The authors assigned a *likely* estimate with *high confidence* to the statement that energy-sector livelihoods would be affected by shifts away from fossil fuel sources driven by emissions-reductions policies; this is because the coal industry has declined undeniably due to market competition, air-quality regulations, non-regulatory decisions made by public and private power utilities, and state and federal climate rules and renewable energy investments. Demand for oil and gas remains stable. The authors assigned a *likely* estimate and *medium confidence* to the statement that climate change will test the adaptive resilience of the region's socially vulnerable residents. This statement is assigned that particular likelihood and confidence because of instances in which recent extreme events have set back rural, Indigenous, and low-income communities, although there is a lack of extensive documentation or literature addressing this risk.

## Key Message 25.4

## Climate Response Involves Navigating Complex Trade-Offs and Tensions

### Description of Evidence Base

The evidence that climate change is creating new and exacerbating existing tensions and trade-offs relies heavily on peer-reviewed literature cited throughout the chapter. There is increasing evidence and examples of how climate change is impacting, and will continue to impact, human communities and natural resources in the Northern Great Plains in complex and interacting ways.[167,219] The region is expected to see higher temperatures, a longer growing season, and shifts in water availability (KM 25.1) that will have impacts on livelihoods, land use, and water quantity and quality (KM 25.3). Climate change may also impact regional demographics over time, driving population growth of urban and amenity communities[9] and the continuing depopulation of rural communities.[5]

The evidence in the peer-reviewed literature indicates that when these impacts are combined, adaptation and mitigation decisions will result in benefits to some individuals and communities and have negative impacts for others. For example, as climate change alters the productivity of existing farmland, some producers are choosing to adapt by planting biofuel energy crops, such as switchgrass (Figure 25.10).[214] The peer-reviewed evidence identifies many benefits for such an action, including sequestration of carbon from the atmosphere,[215,216] sales that exceed current income,[217] and enhanced soil health and resilience

to drought.[218] However, peer-reviewed evidence also indicates that some communities may experience negative impacts, such as the disruption of food production processes, reduced biodiversity, and water competition.[219] Evidence for how decision-makers are navigating these trade-offs is emergent and highly dependent on local context.

Evidence has been well established in the peer-reviewed literature that individual and community knowledge and culture determines how climate change is experienced and managed (KM 20.2). Within this region, the acceptance of human-caused climate change is lower than the national average.[188,189] In a recent nationwide assessment,[187] several states in the region (Wyoming, Colorado, and North Dakota) had curricula that supported the notion that climate change is real and human-caused and can be mitigated, despite reliance on fossil fuel. Lower-scoring states (Montana and Nebraska) failed to link human activities to climate change or stated that climate change is controversial and that educating students about climate change should be the responsibility of parents (South Dakota). As a result of low acceptance and varied educational efforts, discourse in the region focuses on the adaptation and resilience effects of climate action rather than the mitigation effects (KM 25.5). These factors provide evidence of the complicated and shifting landscape for decision-making.

Peer-reviewed demographic and economic literature describes how the regional economy is reliant on agriculture and resource-based sectors (KM 25.3), so adaptation conversations have focused on land-use shifts to alternative crops (Figure 25.10),[214] conversion to grasslands (Figure 25.9),[203,204] and changes in energy infrastructure.[165,205] Many factors complicate the ability of communities in the region to adapt to climate change, but recent peer-reviewed data and literature highlight the high degree of rurality (Figure 25.1) and low capacity to compete for and utilize federal funds (Box 25.1) as particularly inhibiting.

## Major Uncertainties and Research Gaps

Major uncertainties surround the choices that decision-makers and communities will make regarding the management and allocation of resources within the region and the impacts of those choices. There are additional gaps in understanding. For example, increased renewable energy in the region will impact labor opportunities in the region, but little is known on the labor effects of increased renewable energy. Estimates on land area that is required by different energy resources (e.g., wind versus oil) to produce similar amounts of energy are variable. Planning for minimizing grassland fragmentation while developing renewable resources with larger footprints could benefit from more accurate estimates.

## Description of Confidence and Likelihood

Likelihood and confidence statements are based on literature cited in the narrative text, observational data, and collective subject-matter expertise. Confidence for the statement that climate change is leading to decisions that are expected to benefit some and set back others (*very high confidence*) was assigned based on the strong evidence of positive and negative effects of land-use change between agriculture, grassland, and energy in response to changes in climate (e.g., possible negative effects of large-scale conversion to biofuels).[219] Confidence for the statement that decision-makers are navigating a complicated landscape of shifting demographics, policy and regulatory tensions, and barriers to action (*high confidence*) was assigned based on the evidence of policy and decision-making around trade-offs in energy investment and infrastructure development (e.g., state legislation compelling, easing, or resisting energy transition),[167] although it's unclear how widespread such action is. Likelihood was not assigned to these two statements, as the uncertainty associated with human decision- and policymaking is difficult to quantify and is context dependent. For the statement that changes in temperature and precipitation averages, extremes, and seasonality will alter the productivity of working lands, resulting in land-use shifts to alternative crops or conversion to grasslands (*likely*, *medium confidence*), confidence and likelihood were assigned based on evidence of benefits from pilot actions in the region (Figure 25.10), although the scalability of these actions

to large geographies is still an area of study. For the statement that shifts in energy demand, production, and policy will change land-use needs for energy infrastructure (*likely*, *medium confidence*), confidence and likelihood were assigned based on evidence from the literature regarding the transition away from fossil fuel energy systems and its impact on abandonment of infrastructure[165,205] and possible fragmentation of existing grasslands due to new infrastructure.[159]

## Key Message 25.5

## Communities Are Building the Capacity to Adapt and Transform

### Description of Evidence Base

Recent peer-reviewed literature provided the evidence base for adaptation actions being taken around soil health practices in the Northern Great Plains.[245,247] This literature has expanded significantly in recent years; the cited literature describes not only scientific understanding of soil changes and its related adaptive benefits but also research on farmer knowledge networks specific to this region. The evidence base for drought planning also draws from recent peer-reviewed literature and is growing.[261,262] The evidence base for diversification of grass-based livelihoods draws on a more limited peer-reviewed literature base and is more case specific.[217,246] Recent reports and planning efforts provide the evidence base for the newly implemented flood monitoring system in the upper Missouri River basin.[268,269] Reports, planning documents, limited peer-reviewed literature, and conversations with Tribal members provided the evidence for adaptation actions and challenges in rural and Indigenous communities.[271,272,273] A rapidly growing body of peer-reviewed literature provided the evidence for recent advances in ecosystem-based adaptation and scenario planning in the region (Ch. 8).[283,284]

### Major Uncertainties and Research Gaps

Given the already high degree of climatic variability in the region and uncertainty in predicting future conditions, climate adaptation planning is a challenge. Despite these challenges, the evidence base shows that many climate adaptation actions are being tried across the region. In the process of implementing these adaptation actions, one of the major uncertainties is whether planned or implemented actions will ultimately be successful at helping communities or ecosystems adapt to climate change. There is a lack of research evaluating the success of climate adaptation actions, possibly due to insufficient time to judge success or a lack of robust monitoring and evaluation of outcomes. Furthermore, many climate adaptation actions are implemented in very context-dependent situations; therefore, it is uncertain how generalizable some adaptation actions or strategies may be.

### Description of Confidence and Likelihood

It is difficult to quantify adaptation responses and to estimate their numerical variability. Therefore, the authors have not assigned any likelihood estimates to this Key Message. The authors assigned a *medium confidence* rating to the statement about adaptation actions in agricultural communities because there is evidence that a shift toward soil health and other adaptation practices is starting (e.g., Brown 2018;[245] Zilverberg et al. 2018[247]), but widespread adoption of these practices is not yet a reality. The authors assigned a *high confidence* rating to the third statement because there is good evidence that several Tribal Nations are leading efforts to incorporate Traditional Knowledge and governance into their adaptation plans (e.g., Blackfeet Nation 2018;[271] CSKT 2016;[272] Sicangu Climate Crisis Working Group 2022[273]). The statement about adaptation planning for natural resource managers is assigned a *medium confidence* rating because scenario planning is a well-developed tool and gaining traction in the National Park Service (e.g., Ch. 8),[283,284] but it is not yet being used widely outside of the National Park Service.

# References


1. Briske, D.D., J.P. Ritten, A.R. Campbell, T. Klemm, and A.E.H. King, 2021: Future climate variability will challenge rangeland beef cattle production in the Great Plains. *Rangelands*, **43** (1), 29–36. https://doi.org/10.1016/j.rala.2020.11.001

2. Miller, A.B., P.L. Winter, J.J. Sánchez, D.L. Peterson, and J.W. Smith, 2022: Climate change and recreation in the western United States: Effects and opportunities for adaptation. *Journal of Forestry*, **120** (4), 453–472. https://doi.org/10.1093/jofore/fvab072

3. Wienhold, B.J., M.F. Vigil, J.R. Hendrickson, and J.D. Derner, 2018: Vulnerability of crops and croplands in the US Northern Plains to predicted climate change. *Climatic Change*, **146** (1), 219–230. https://doi.org/10.1007/s10584-017-1989-x

4. Husa, A. and C.E. Morse, 2020: Rurality as a key factor for place attachment in the Great Plains. *Geographical Review*, **112** (1), 27–45. https://doi.org/10.1080/00167428.2020.1786384

5. BEA, 2021: Regional Economic Accounts. U.S. Department of Commerce, Bureau of Economic Analysis. https://www.bea.gov/data/economic-accounts/regional

6. Wilson, R., 2020: Moving to economic opportunity: The migration response to the fracking boom. *Journal of Human Resources*, **57** (3), 918–955. https://doi.org/10.3368/jhr.57.3.0817-8989r2

7. ERS. 2015: County Typology Codes. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/data-products/county-typology-codes/

8. U.S. Census Bureau, 2020: American Community Survey (ACS). U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/programs-surveys/acs

9. Dimke, C., M.C. Lee, and J. Bayham, 2021: COVID-19 and the renewed migration to the rural West. *Western Economics Forum*, **19** (1), 89–102. https://doi.org/10.22004/ag.econ.311309

10. Gilio-Whitaker, D., 2019: *As Long as Grass Grows: The Indigenous Fight for Environmental Justice, from Colonization to Standing Rock*. Beacon Press. http://www.beacon.org/as-long-as-grass-grows-p1445.aspx

11. Shamon, H., O.G. Cosby, C.L. Andersen, H. Augare, J. BearCub Stiffarm, C.E. Bresnan, B.L. Brock, E. Carlson, J.L. Deichmann, A. Epps, N. Guernsey, C. Hartway, D. Jørgensen, W. Kipp, D. Kinsey, K.J. Komatsu, K. Kunkel, R. Magnan, J.M. Martin, and T.S. Akre, 2022: The potential of bison restoration as an ecological approach to future tribal food sovereignty on the northern Great Plains. *Frontiers in Ecology and Evolution*, **10**, 1–15. https://doi.org/10.3389/fevo.2022.826282

12. Cain, C., 2021: Ch. 33. Developing climatic capacity in rural places. In: *Investing In Rural Prosperity*. Dumont, A. and D.P. Davis, Eds. Federal Reserve Bank of St. Louis, 475–486. https://www.stlouisfed.org/-/media/project/frbstl/stlouisfed/files/pdfs/community-development/investing-rural/chapters/chapter33.pdf

13. ERS, 2019: Frontier and Remote Area Codes. U.S. Department of Agriculture, Economic Research Service, accessed May 24, 2023. https://www.ers.usda.gov/data-products/frontier-and-remote-area-codes/

14. Frankson, R., K.E. Kunkel, S.M. Champion, D.R. Easterling, and K. Jencso, 2022: Montana State Climate Summary 2022. NOAA Technical Report NESDIS 150-MT. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/mt/

15. Frankson, R., K.E. Kunkel, S.M. Champion, D.R. Easterling, N.A. Umphlett, and C.J. Stiles, 2022: South Dakota State Climate Summary 2022. NOAA Technical Report NESDIS 150-SD. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/sd/

16. Frankson, R., K.E. Kunkel, L.E. Stevenes, D.R. Easterling, M. Shulski, A. Akyüz, N.A. Umphlett, and C.J. Stiles, 2022: North Dakota State Climate Summary 2022. NOAA Technical Report NESDIS 150-ND. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/nd/

17. Frankson, R., K.E. Kunkel, L.E. Stevens, D.R. Easterling, B.C. Stewart, N.A. Umphlett, and C.J. Stiles, 2022: Wyoming State Climate Summary 2022. NOAA Technical Report NESDIS 150-WY. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/wy/

18. Frankson, R., K.E. Kunkel, L.E. Stevens, M. Shulski, N.A. Umphlett, and C.J. Stiles, 2022: Nebraska State Climate Summary 2022. NOAA Technical Report NESDIS 150-NE. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/ne/

19. Siirila-Woodburn, E.R., A.M. Rhoades, B.J. Hatchett, L.S. Huning, J. Szinai, C. Tague, P.S. Nico, D.R. Feldman, A.D. Jones, W.D. Collins, and L. Kaatz, 2021: A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment*, **2** (11), 800–819. https://doi.org/10.1038/s43017-021-00219-y

20. Krajick, K., 2018: The 100th meridian, where the Great Plains begin, may be shifting: Warming climate may be moving western aridity eastward. Columbia University, Columbia Climate School: Climate, Earth, and Society, New York, NY, April 11, 2018. https://news.climate.columbia.edu/2018/04/11/the-100th-meridian-where-the-great-plains-used-to-begin-now-moving-east/

21. Seager, R., J. Feldman, N. Lis, M. Ting, A.P. Williams, J. Nakamura, H. Liu, and N. Henderson, 2018: Whither the 100th meridian? The once and future physical and human geography of America's arid–humid divide. Part II: The meridian moves east. *Earth Interactions*, **22** (5), 1–24. https://doi.org/10.1175/ei-d-17-0012.1

22. Swain, S. and K. Hayhoe, 2015: CMIP5 projected changes in spring and summer drought and wet conditions over North America. *Climate Dynamics*, **44** (9), 2737–2750. https://doi.org/10.1007/s00382-014-2255-9

23. Landers, J., 2021: P3 improves US Army Corps' Midwest flood-diversion project. *Civil Engineering Magazine*. https://www.asce.org/publications-and-news/civil-engineering-source/civil-engineering-magazine/article/2021/08/p3-improves-us-army-corps-midwest-flood-diversion-project

24. Jacobs, J., 2011: The sustainability of water resources in the Colorado River Basin. *Bridge*, **41** (4), 6–12. https://www.nae.edu/19582/bridge/55183/55194.aspx

25. UCRC, 2021: The Seventy-Second Annual Report of the Upper Colorado River Commission. Upper Colorado River Commission, Salt Lake City, UT, 161 pp. http://www.ucrcommission.com/wp-content/uploads/2021/06/UCRC-WY2020-Annual-Report-Final-June-10-2021.pdf

26. Udall, B. and J. Overpeck, 2017: The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, **53** (3), 2404–2418. https://doi.org/10.1002/2016wr019638

27. McCabe, G.J., D.M. Wolock, G.T. Pederson, C.A. Woodhouse, and S. McAfee, 2017: Evidence that recent warming is reducing upper Colorado River flows. *Earth Interactions*, **21** (10), 1–14. https://doi.org/10.1175/ei-d-17-0007.1

28. Raupach, T.H., O. Martius, J.T. Allen, M. Kunz, S. Lasher-Trapp, S. Mohr, K.L. Rasmussen, R.J. Trapp, and Q. Zhang, 2021: The effects of climate change on hailstorms. *Nature Reviews Earth & Environment*, **2** (3), 213–226. https://doi.org/10.1038/s43017-020-00133-9

29. Tang, B.H., V.A. Gensini, and C.R. Homeyer, 2019: Trends in United States large hail environments and observations. *Climate and Atmospheric Science*, **2** (1), 1–7. https://doi.org/10.1038/s41612-019-0103-7

30. Childs, S.J., R.S. Schumacher, and S.M. Strader, 2020: Projecting end-of-century human exposure from tornadoes and severe hailstorms in eastern Colorado: Meteorological and population perspectives. *Weather, Climate, and Society*, **12** (3), 575–595. https://doi.org/10.1175/wcas-d-19-0153.1

31. Lepore, C., R. Abernathey, N. Henderson, J.T. Allen, and M.K. Tippett, 2021: Future global convective environments in CMIP6 models. *Earth's Future*, **9** (12), e2021EF002277. https://doi.org/10.1029/2021ef002277

32. Rasmussen, K.L., A.F. Prein, R.M. Rasmussen, K. Ikeda, and C. Liu, 2020: Changes in the convective population and thermodynamic environments in convection-permitting regional climate simulations over the United States. *Climate Dynamics*, **55** (1), 383–408. https://doi.org/10.1007/s00382-017-4000-7

33. Trapp, R.J., K.A. Hoogewind, and S. Lasher-Trapp, 2019: Future changes in hail occurrence in the United States determined through convection-permitting dynamical downscaling. *Journal of Climate*, **32** (17), 5493–5509. https://doi.org/10.1175/jcli-d-18-0740.1

34. Brimelow, J.C., W.R. Burrows, and J.M. Hanesiak, 2017: The changing hail threat over North America in response to anthropogenic climate change. *Nature Climate Change*, **7**, 516–522. https://doi.org/10.1038/nclimate3321

35. Haberlie, A.M., W.S. Ashley, C.M. Battisto, and V.A. Gensini, 2022: Thunderstorm activity under intermediate and extreme climate change scenarios. *Geophysical Research Letters*, **49** (14), e2022GL098779. https://doi.org/10.1029/2022gl098779

36. Barth, N.A., K.R. Ryberg, A. Gregory, and A.G. Blum, 2022: Ch. A. Introduction to attribution of monotonic trends and change points in peak streamflow across the conterminous United States using a multiple working hypotheses framework, 1941–2015 and 1966–2015. In: *Attribution of Monotonic Trends and Change Points in Peak Streamflow Across the Conterminous United States Using a Multiple Working Hypotheses Framework, 1941–2015 and 1966–2015*. Ryberg, K.R., Ed. U.S. Geological Survey, Reston, VA, A1–A29. https://doi.org/10.3133/pp1869

37. Berghuijs, W.R., R.A. Woods, C.J. Hutton, and M. Sivapalan, 2016: Dominant flood generating mechanisms across the United States. *Geophysical Research Letters*, **43** (9), 4382–4390. https://doi.org/10.1002/2016gl068070

38. Livneh, B., M. Hoerling, A. Badger, and J. Eischeid, 2016: Climate Assessment Report: Causes for Hydrologic Extremes in the Upper Missouri River Basin. National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Earth System Research Laboratory, Boulder, CO. https://www.esrl.noaa.gov/psd/csi/factsheets/pdf/mrb-climate-assessment-report-hydroextremes_2016.pdf

39. Ryberg, K.R., A.V. Vecchia, F.A. Akyüz, and W. Lin, 2016: Tree-ring-based estimates of long-term seasonal precipitation in the Souris River Region of Saskatchewan, North Dakota and Manitoba. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques*, **41** (3), 412–428. https://doi.org/10.1080/07011784.2016.1164627

40. Spotted Eagle, F. and J. Veilleux, 2021: Land and water policy in the Missouri River Basin from Indigenous perspectives. *Water Resources Impact*, **23** (2), 7–12. https://online.flippingbook.com/view/446296713/8

41. NCEI, 2022: U.S. Billion-Dollar Weather and Climate Disasters: Disaster and Risk Mapping. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncdc.noaa.gov/billions/mapping

42. Hoell, A., M. Hoerling, X.-W. Quan, and R. Robinson, 2023: Recent high Missouri River Basin runoff was unlikely due to climate change. *Journal of Applied Meteorology and Climatology*, **62** (6), 657–675. https://doi.org/10.1175/jamc-d-22-0158.1

43. Sando, T.R., S.K. Sando, K.R. Ryberg, and K.J. Chase, 2022: Ch. C. Attribution of monotonic trends and change points in peak streamflow in the Upper Plains Region of the United States, 1941–2015 and 1966–2015. In: *Attribution of Monotonic Trends and Change Points in Peak Streamflow Across the Conterminous United States Using a Multiple Working Hypotheses Framework, 1941–2015 and 1966–2015*. Ryberg, K.R., Ed. U.S. Geological Survey, Reston, VA. https://doi.org/10.3133/pp1869

44. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

45. Peters, M.P. and L.R. Iverson, 2019: Ch. 2. Projected drought for the conterminous United States in the 21st century. In: *Effects of Drought on Forests and Rangelands in the United States: Translating Science Into Management Responses*. Vose, J.M., D.L. Peterson, C.H. Luce, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 19–39. https://www.fs.usda.gov/treesearch/pubs/59161

46. Robertson, D.M., H.A. Perlman, and T.N. Narisimhan, 2022: Ch. 4. Hydrological cycle and water budgets. In: *Encyclopedia of Inland Waters*, 2nd ed. Mehner, T. and K. Tockner, Eds. Elsevier, Oxford, UK, 19–27. https://doi.org/10.1016/b978-0-12-819166-8.00008-6

47. Cook, B.I., T.R. Ault, and J.E. Smerdon, 2015: Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances*, **1** (1), e1400082. https://doi.org/10.1126/sciadv.1400082

48. Hanberry, B., M.C. Reeves, A. Brischke, M. Hannemann, T. Hudson, R. Mayberry, D. Ojima, H.R. Prendeville, and I. Rangwala, 2019: Ch. 7. Managing effects of drought in the Great Plains. In: *Effects of Drought on Forests and Rangelands in the United States: Translating Science Into Management Responses*. Vose, J.M., D.L. Peterson, C.H. Luce, T. Patel-Weynand, E.J.M. Vose, D.L. Peterson, C.H. Luce, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 141–164. https://www.fs.usda.gov/research/treesearch/59166

49. Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande, 2017: Ch. 8. Droughts, floods, and wildfires. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 231–256. https://doi.org/10.7930/j0cj8bnn

50. Hoell, A., J. Perlwitz, C. Dewes, K. Wolter, I. Rangwala, X.W. Quan, and J. Eisceid, 2019: Anthropogenic contributions to the intensity of the 2017 United States Northern Great Plains drought. *Bulletin of the American Meteorological Society*, **100** (1), 19–24. https://doi.org/10.1175/bams-d-18-0127.1

51. Martin, J.T., G.T. Pederson, C.A. Woodhouse, E.R. Cook, G.J. McCabe, K.J. Anchukaitis, E.K. Wise, P.J. Erger, L. Dolan, M. McGuire, S. Gangopadhyay, K.J. Chase, J.S. Littell, S.T. Gray, S. St. George, J.M. Friedman, D.J. Sauchyn, J.-M. St-Jacques, and J. King, 2020: Increased drought severity tracks warming in the United States' largest river basin. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (21), 11328–11336. https://doi.org/10.1073/pnas.1916208117

52. Christian, J.I., J.B. Basara, J.A. Otkin, and E.D. Hunt, 2019: Regional characteristics of flash droughts across the United States. *Environmental Research Communications*, **1** (12), 125004. https://doi.org/10.1088/2515-7620/ab50ca

53. Otkin, J.A., M. Svoboda, E.D. Hunt, T.W. Ford, M.C. Anderson, C. Hain, and J.B. Basara, 2018: Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bulletin of the American Meteorological Society*, **99** (5), 911–919. https://doi.org/10.1175/bams-d-17-0149.1

54. Liu, Y., S.L. Goodrick, and J.A. Stanturf, 2013: Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. *Forest Ecology and Management*, **294**, 120–135. https://doi.org/10.1016/j.foreco.2012.06.049

55. Clarke, H., T. Penman, M. Boer, G.J. Cary, J.B. Fontaine, O. Price, and R. Bradstock, 2020: The proximal drivers of large fires: A pyrogeographic study. *Frontiers in Earth Science*, **8**, 90. https://doi.org/10.3389/feart.2020.00090

56. Littell, J.S., D.L. Peterson, K.L. Riley, Y. Liu, and C.H. Luce, 2016: A review of the relationships between drought and forest fire in the United States. *Global Change Biology*, **22** (7), 2353–2369. https://doi.org/10.1111/gcb.13275

57. Donovan, V.M., C.L. Wonkka, and D. Twidwell, 2017: Surging wildfire activity in a grassland biome. *Geophysical Research Letters*, **44** (12), 5986–5993. https://doi.org/10.1002/2017gl072901

58. Westerling, A.L., 2016: Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371** (1696), 20150178. https://doi.org/10.1098/rstb.2015.0178

59. Knapp, E.E., B.L. Estes, and C.N. Skinner, 2009: Ecological Effects of Prescribed Fire Season: A Literature Review and Synthesis for Managers. Gen. Tech. Rep. PSW-GTR-224. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, 80 pp. https://doi.org/10.2737/psw-gtr-224

60. Knowles, N., 2015: Trends in snow cover and related quantities at weather stations in the conterminous United States. *Journal of Climate*, **28** (19), 7518–7528. https://doi.org/10.1175/jcli-d-15-0051.1

61. Adams, A., R. Byron, B. Maxwell, S. Higgins, M. Eggers, L. Byron, and C. Whitlock, 2021: Climate Change and Human Health in Montana: A Special Report of the Montana Climate Assessment. Montana State University, Institute on Ecosystems, Center for American Indian and Rural Health Equity, Bozeman, MT, 216 pp. https://doi.org/10.15788/c2h22021

62. Palinkas, L.A. and M. Wong, 2020: Global climate change and mental health. *Current Opinion in Psychology*, **32**, 12–16. https://doi.org/10.1016/j.copsyc.2019.06.023

63. Hedegaard, H., S.C. Curtin, and M. Warner, 2021: Suicide Mortality in the United States, 1999–2019. NCHS Data Brief, No 398. Centers for Disease Control and Prevention, National Center for Health Statistics, Hyattsville, MD. https://doi.org/10.15620/cdc:101761

64. Ivey-Stephenson, A.Z., A.E. Crosby, S.P. Jack, T. Haileyesus, and M. Kresnow-Sedacca, 2017: Suicide trends among and within urbanization levels by sex, race/ethnicity, age group, and mechanism of death — United States, 2001–2015. *MMWR Surveillance Summaries*, **66** (18), 1–16. https://doi.org/10.15585/mmwr.ss6618a1

65. Bjornestad, A., C. Cuthbertson, and J. Hendricks, 2021: An analysis of suicide risk factors among farmers in the Midwestern United States. *International Journal of Environmental Research and Public Health*, **18** (7), 3563. https://doi.org/10.3390/ijerph18073563

66. Nestadt, P.S., P. Triplett, D.R. Fowler, and R. Mojtabai, 2017: Urban–rural differences in suicide in the state of Maryland: The role of firearms. *American Journal of Public Health*, **107** (10), 1548–1553. https://doi.org/10.2105/ajph.2017.303865

67. Burke, M., F. González, P. Baylis, S. Heft-Neal, C. Baysan, S. Basu, and S. Hsiang, 2018: Higher temperatures increase suicide rates in the United States and Mexico. *Nature Climate Change*, **8** (8), 723–729. https://doi.org/10.1038/s41558-018-0222-x

68. Yazd, S.D., S.A. Wheeler, and A. Zuo, 2019: Key risk factors affecting farmers' mental health: A systematic review. *International Journal of Environmental Research and Public Health*, **16** (23), 4849. https://doi.org/10.3390/ijerph16234849

69. Howard, M., S. Ahmed, P. Lachapelle, and M.B. Schure, 2020: Farmer and rancher perceptions of climate change and their relationships with mental health. *Journal of Rural Mental Health*, **44** (2), 87–95. https://doi.org/10.1037/rmh0000131

70. Albrecht, G., G.-M. Sartore, L. Connor, N. Higginbotham, S. Freeman, B. Kelly, H. Stain, A. Tonna, and G. Pollard, 2007: Solastalgia: The distress caused by environmental change. *Australasian Psychiatry*, **15** (Sup1), S95–S98. https://doi.org/10.1080/10398560701701288

71. Galway, L.P., T. Beery, K. Jones-Casey, and K. Tasala, 2019: Mapping the solastalgia literature: A scoping review study. *International Journal of Environmental Research and Public Health*, **16** (15), 2662. https://doi.org/10.3390/ijerph16152662

72. The World Bank, 2023: Understanding Poverty: Indigenous Peoples. World Bank Group, accessed April 4, 2023. https://www.worldbank.org/en/topic/indigenouspeoples

73. Ellis, N.R. and G.A. Albrecht, 2017: Climate change threats to family farmers' sense of place and mental wellbeing: A case study from the Western Australian Wheatbelt. *Social Science & Medicine*, **175**, 161–168. https://doi.org/10.1016/j.socscimed.2017.01.009

74. Cajete, G.A., 2020: Indigenous science, climate change, and Indigenous community building: A framework of foundational perspectives for Indigenous community resilience and revitalization. *Sustainability*, **12** (22), 9569. https://doi.org/10.3390/su12229569

75. Doyle, J.T., M.H. Redsteer, and M.J. Eggers, 2013: Exploring effects of climate change on Northern Plains American Indian health. *Climatic Change*, **120** (3), 643–655. https://doi.org/10.1007/s10584-013-0799-z

76. Martin, C., J. Doyle, J. LaFrance, M.J. Lefthand, S.L. Young, E. Three Irons, and M.J. Eggers, 2020: Change rippling through our waters and culture. *Journal of Contemporary Water Research & Education*, **169** (1), 61–78. https://doi.org/10.1111/j.1936-704x.2020.03332.x

77. O'Dell, K., B. Ford, E.V. Fischer, and J.R. Pierce, 2019: Contribution of wildland-fire smoke to us $PM_{2.5}$ and its influence on recent trends. *Environmental Science Technology*, **53** (4), 1797–1804. https://doi.org/10.1021/acs.est.8b05430

78. NWS, 2021: Weather Related Fatality and Injury Statistics. National Oceanic and Atmospheric Administration, National Weather Service. https://www.weather.gov/hazstat/

79. Dahl, K. and R. Licker, 2021: Too Hot to Work: Assessing the Threats Climate Change Poses to Outdoor Workers. Union of Concerned Scientists, Cambridge, MA. https://doi.org/10.47923/2021.14236

80. Harrigan, R.J., H.A. Thomassen, W. Buermann, and T.B. Smith, 2014: A continental risk assessment of West Nile virus under climate change. *Global Change Biology*, **20** (8), 2417–2425. https://doi.org/10.1111/gcb.12534

81. Paull, S.H., D.E. Horton, M. Ashfaq, D. Rastogi, L.D. Kramer, N.S. Diffenbaugh, and A.M. Kilpatrick, 2017: Drought and immunity determine the intensity of West Nile virus epidemics and climate change impacts. *Proceedings of the Royal Society B: Biological Sciences*, **284** (1848). https://doi.org/10.1098/rspb.2016.2078

82. Smith, K.H., A.J. Tyre, J. Hamik, M.J. Hayes, Y. Zhou, and L. Dai, 2020: Using climate to explain and predict West Nile virus risk in Nebraska. *GeoHealth*, **4** (9), e2020GH000244. https://doi.org/10.1029/2020gh000244

83. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

84. Kuhn, K.G., K.M. Nygård, B. Guzman-Herrador, L.S. Sunde, R. Rimhanen-Finne, L. Trönnberg, M.R. Jepsen, R. Ruuhela, W.K. Wong, and S. Ethelberg, 2020: Campylobacter infections expected to increase due to climate change in Northern Europe. *Scientific Reports*, **10** (1), 13874. https://doi.org/10.1038/s41598-020-70593-y

85. Koks, E., 2018: Moving flood risk modelling forwards. *Nature Climate Change*, **8**, 561–562. https://doi.org/10.1038/s41558-018-0185-y

86. Räsänen, A., S. Juhola, A. Nygren, M. Käkönen, M. Kallio, A.M. Monge, and M. Kanninen, 2016: Climate change, multiple stressors and human vulnerability: A systematic review. *Regional Environmental Change*, **16**, 2291–2302. https://doi.org/10.1007/s10113-016-0974-7

87. Williams, A.P., B. Livneh, K.A. McKinnon, W.D. Hansen, J.S. Mankin, B.I. Cook, J.E. Smerdon, A.M. Varuolo-Clarke, N.R. Bjarke, C.S. Juang, and D.P. Lettenmaier, 2022: Growing impact of wildfire on western US water supply. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (10), 2114069119. https://doi.org/10.1073/pnas.2114069119

88. Coughlan, M.R., A. Ellison, and A.H. Cavanaugh, 2019: Social Vulnerability and Wildfire in the Wildland Urban Interface: Literature Synthesis. University of Oregon, Northwest Fire Science Consortium, 24 pp. https://scholarsbank.uoregon.edu/xmlui/handle/1794/25359

89. Pohl, K., 2021: The Unequal Impacts of Wildfire. Headwaters Economics, Bozeman, MT. https://headwaterseconomics.org/natural-hazards/unequal-impacts-of-wildfire/

90. Ryberg, K.R. and J.G. Chanat, 2022: Climate extremes as drivers of surface-water-quality trends in the United States. *Science of The Total Environment*, **809**, 152165. https://doi.org/10.1016/j.scitotenv.2021.152165

91. Stets, E.G., L.A. Sprague, G.P. Oelsner, H.M. Johnson, J.C. Murphy, K. Ryberg, A.V. Vecchia, R.E. Zuellig, J.A. Falcone, and M.L. Riskin, 2020: Landscape drivers of dynamic change in water quality of U.S. rivers. *Environmental Science & Technology*, **54** (7), 4336–4343. https://doi.org/10.1021/acs.est.9b05344

92. Murphy, J.C., R.M. Hirsch, and L.A. Sprague, 2014: Antecedent flow conditions and nitrate concentrations in the Mississippi River Basin. *Hydrology and Earth System Sciences*, **10** (3), 967–979. https://doi.org/10.5194/hessd-10-11451-2013

93. Lu, C., J. Zhang, H. Tian, W.G. Crumpton, M.J. Helmers, W.-J. Cai, C.S. Hopkinson, and S.E. Lohrenz, 2020: Increased extreme precipitation challenges nitrogen load management to the Gulf of Mexico. *Communications Earth & Environment*, **1** (1), 21. https://doi.org/10.1038/s43247-020-00020-7

94. Michalak, A.M., 2016: Study role of climate change in extreme threats to water quality. *Nature*, **535** (7612), 349–350. https://doi.org/10.1038/535349a

95. Otten, T.G. and H.W. Paerl, 2015: Health effects of toxic cyanobacteria in U.S. drinking and recreational waters: Our current understanding and proposed direction. *Current Environmental Health Reports*, **2** (1), 75–84. https://doi.org/10.1007/s40572-014-0041-9

96. EPA, 2022: Nutrient Pollution: Climate Change and Harmful Algal Blooms. U.S. Environmental Protection Agency, accessed February 14, 2022. https://www.epa.gov/nutrientpollution/climate-change-and-harmful-algal-blooms

97. Laughrey, Z.R., V.G. Christensen, R.J. Dusek, S. Senegal, J.S. Lankton, T.A. Ziegler, L.C. Jones, D.K. Jones, B.M. Williams, S. Gordon, G.A. Clyde, E.B. Emery, and K.A. Loftin, 2022: A review of algal toxin exposures on reserved federal lands and among trust species in the United States. *Critical Reviews in Environmental Science and Technology*, **52** (23), 4284–4307. https://doi.org/10.1080/10643389.2021.2010511

98. Wheeling, K., 2019: Toxic algal blooms are worsening with climate change. *Eos*, **100**. https://doi.org/10.1029/2019eo136398

99. Lark, T.J., S.A. Spawn, M. Bougie, and H.K. Gibbs, 2020: Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nature Communications*, **11** (1), 4295. https://doi.org/10.1038/s41467-020-18045-z

100. Hendrickson, J.R., K.K. Sedivec, D. Toledo, and J. Printz, 2019: Challenges facing grasslands in the northern Great Plains and north central region. *Rangelands*, **41** (1), 23–29. https://doi.org/10.1016/j.rala.2018.11.002

101. Palit, R., G. Gramig, and E.S. DeKeyser, 2021: Kentucky bluegrass invasion in the northern Great Plains and prospective management approaches to mitigate its spread. *Plants*, **10** (4), 817. https://doi.org/10.3390/plants10040817

102. Niemuth, N.D., M.E. Estey, S.P. Fields, B. Wangler, A.A. Bishop, P.J. Moore, R.C. Grosse, and A.J. Ryba, 2017: Developing spatial models to guide conservation of grassland birds in the U.S. Northern Great Plains. *The Condor*, **119** (3), 506–525. https://doi.org/10.1650/condor-17-14.1

103. Pulliam, J.P., S. Somershoe, M. Sather, and L.B. McNew, 2020: Habitat targets for imperiled grassland birds in northern mixed-grass prairie. *Rangeland Ecology & Management*, **73** (4), 511–519. https://doi.org/10.1016/j.rama.2020.02.006

104. Bateman, B.L., C. Wilsey, L. Taylor, J. Wu, G.S. LeBaron, and G. Langham, 2020: North American birds require mitigation and adaptation to reduce vulnerability to climate change. *Conservation Science and Practice*, **2** (8), 242. https://doi.org/10.1111/csp2.242

105. Otto, C.R.V., H. Zheng, A.L. Gallant, R. Iovanna, B.L. Carlson, M.D. Smart, and S. Hyberg, 2018: Past role and future outlook of the Conservation Reserve Program for supporting honey bees in the Great Plains. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (29), 7629–7634. https://doi.org/10.1073/pnas.1800057115

106. Durant, J.L. and C.R.V. Otto, 2019: Feeling the sting? Addressing land-use changes can mitigate bee declines. *Land Use Policy*, **87**, 104005. https://doi.org/10.1016/j.landusepol.2019.05.024

107. Otto, C.R.V., C.L. Roth, B.L. Carlson, and M.D. Smart, 2016: Land-use change reduces habitat suitability for supporting managed honey bee colonies in the Northern Great Plains. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (37), 10430–10435. https://doi.org/10.1073/pnas.1603481113

108. Niemuth, N.D., B. Wangler, J.J. LeBrun, D. Dewald, S. Larson, T. Schwagler, C. Bradbury, R.D. Pritchert, and R. Iovanna, 2021: Conservation planning for pollinators in the U.S. Great Plains: Considerations of context, treatments, and scale. *Ecosphere*, **12** (7), 03556. https://doi.org/10.1002/ecs2.3556

109. Miller Hesed, C. and H. Yocum, 2023: Grassland Management Priorities for the North Central Region. USGS Open-File Report 2023–1037. U.S. Geological Survey, 53 pp. https://doi.org/10.3133/ofr20231037

110. Miller Hesed, C.D., H.M. Yocum, I. Rangwala, A.J. Symstad, J.M. Martin, K. Ellison, D.J.A. Wood, M. Ahlering, K.J. Chase, S. Crausbay, A.D. Davidson, J. Elliott, J. Giocomo, D.L. Hoover, T. Klemm, D. Lightfoot, O.P. McKenna, B.W. Miller, D. Mosher, R.C. Nagy, J.B. Nippert, J. Pittman, L. Porensky, J. Stephens, and A.V. Zale, 2023: Synthesis of Climate and Ecological Science to Support Grassland Management Priorities in the North Central Region. USGS Open-File Report 2023–1036. U.S. Geological Survey, 21 pp. https://doi.org/10.3133/ofr20231036

111. NRCS, 2018: National Resources Inventory Rangeland Resource Assessment. U.S. Department of Agriculture, Natural Resources Conservation Service, 624 pp. https://www.nrcs.usda.gov/sites/default/files/2022-10/RangelandReport2018_0.pdf

112. U.S. Census Bureau. 2021: County Business Patterns 2019. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/datasets/2019/econ/cbp/2019-cbp.html

113. Arora, G., H. Feng, C.J. Anderson, and D.A. Hennessy, 2020: Evidence of climate change impacts on crop comparative advantage and land use. *Agricultural Economics*, **51** (2), 221–236. https://doi.org/10.1111/agec.12551

114. Kukal, M.S. and S. Irmak, 2018: U.S. agro-climate in 20th century: Growing degree days, first and last frost, growing season length, and impacts on crop yields. *Scientific Reports*, **8** (1), 6977. https://doi.org/10.1038/s41598-018-25212-2

115. Rosenzweig, S.T. and M.E. Schipanski, 2019: Landscape-scale cropping changes in the High Plains: Economic and environmental implications. *Environmental Research Letters*, **14** (12), 124088. https://doi.org/10.1088/1748-9326/ab5e8b

116. Vick, E.S.K., P.C. Stoy, A.C.I. Tang, and T. Gerken, 2016: The surface-atmosphere exchange of carbon dioxide, water, and sensible heat across a dryland wheat-fallow rotation. *Agriculture, Ecosystems & Environment*, **232**, 129–140. https://doi.org/10.1016/j.agee.2016.07.018

117. Berg, A., J. Sheffield, and P.C.D. Milly, 2017: Divergent surface and total soil moisture projections under global warming. *Geophysical Research Letters*, **44** (1), 236–244. https://doi.org/10.1002/2016gl071921

118. Rigden, A.J., N.D. Mueller, N.M. Holbrook, N. Pillai, and P. Huybers, 2020: Combined influence of soil moisture and atmospheric evaporative demand is important for accurately predicting US maize yields. *Nature Food*, **1**, 127–133. https://doi.org/10.1038/s43016-020-0028-7

119. Zhu, P., T. Kim, Z. Jin, C. Lin, X. Wang, P. Ciais, N.D. Mueller, A. Aghakouchak, J. Huang, D. Mulla, and D. Makowski, 2022: The critical benefits of snowpack insulation and snowmelt for winter wheat productivity. *Nature Climate Change*, **12** (5), 485–490. https://doi.org/10.1038/s41558-022-01327-3

120. Ainsworth, E.A. and S.P. Long, 2021: 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation? *Global Change Biology*, **27** (1), 27–49. https://doi.org/10.1111/gcb.15375

121. Lombardozzi, D.L., G.B. Bonan, S. Levis, and D.M. Lawrence, 2018: Changes in wood biomass and crop yields in response to projected $CO_2$, $O_3$, nitrogen deposition, and climate. *Journal of Geophysical Research: Biogeosciences*, **123** (10), 3262–3282. https://doi.org/10.1029/2018jg004680

122. Sloat, L.L., S.J. Davis, J.S. Gerber, F.C. Moore, D.K. Ray, P.C. West, and N.D. Mueller, 2020: Climate adaptation by crop migration. *Nature Communications*, **11** (1), 1243. https://doi.org/10.1038/s41467-020-15076-4

123. Mertens, A., J. Van Meensel, L. Willem, L. Lauwers, and J. Buysse, 2018: Ensuring continuous feedstock supply in agricultural residue value chains: A complex interplay of five influencing factors. *Biomass and Bioenergy*, **109**, 209–220. https://doi.org/10.1016/j.biombioe.2017.12.024

124. Kant, J.M., G.E. Larson, S.R. Burckhard, B.W. Berdanier, and R.T. Meyers, 2015: Contemporary use of wild fruits by the Lakota in South Dakota and implications for cultural identity. *Great Plains Research*, **25** (1), 13–24. https://doi.org/10.1353/gpr.2015.0011

125. Yuzicapi, L., F. Gendron, and R. Bouch-van Dusen, 2013: Dakota and Lakota traditional food and tea: Teachings from elder Lorraine Yuzicapi. *Pimatisiwin: A Journal of Aboriginal and Indigenous Community Health*, **11** (1), 65–97. https://iportal.usask.ca/record/35678

126. Hoell, A., B.A. Parker, M. Downey, N. Umphlett, K. Jencso, F.A. Akyuz, D. Peck, T. Hadwen, B. Fuchs, D. Kluck, L. Edwards, J. Perlwitz, J. Eischeid, V. Deheza, R. Pulwarty, and K. Bevington, 2020: Lessons learned from the 2017 flash drought across the U.S. Northern Great Plains and Canadian Prairies. *Bulletin of the American Meteorological Society*, **101** (12), 2171–2185. https://doi.org/10.1175/bams-d-19-0272.1

127. McKenna, O.P., D.M. Mushet, D.O. Rosenberry, and J.W. LaBaugh, 2017: Evidence for a climate-induced ecohydrological state shift in wetland ecosystems of the southern Prairie Pothole Region. *Climatic Change*, **145**, 273–287. https://doi.org/10.1007/s10584-017-2097-7

128. Sohl, T., J. Dornbierer, and S. Wika, 2019: Linking landscapes and people—Projecting the future of the Great Plains. *Rangelands*, **41** (2), 79–87. https://doi.org/10.1016/j.rala.2018.12.001

129. Hufkens, K., T.F. Keenan, L.B. Flanagan, R.L. Scott, C.J. Bernacchi, E. Joo, N.A. Brunsell, J. Verfaillie, and A.D. Richardson, 2016: Productivity of North American grasslands is increased under future climate scenarios despite rising aridity. *Nature Climate Change*, **6**, 710–714. https://doi.org/10.1038/nclimate2942

130. Klemm, T., D.D. Briske, and M.C. Reeves, 2020: Potential natural vegetation and NPP responses to future climates in the U.S. Great Plains. *Ecosphere*, **11** (10), 03264. https://doi.org/10.1002/ecs2.3264

131. Reeves, M.C., A.L. Moreno, K.E. Bagne, and S.W. Running, 2014: Estimating climate change effects on net primary production of rangelands in the United States. *Climatic Change*, **126** (3), 429–442. https://doi.org/10.1007/s10584-014-1235-8

132. Augustine, D.J., D.M. Blumenthal, T.L. Springer, D.R. LeCain, S.A. Gunter, and J.D. Derner, 2018: Elevated $CO_2$ induces substantial and persistent declines in forage quality irrespective of warming in mixedgrass prairie. *Ecological Applications*, **28** (3), 721–735. https://doi.org/10.1002/eap.1680

133. Milchunas, D.G., A.R. Mosier, J.A. Morgan, D.R. LeCain, J.Y. King, and J.A. Nelson, 2005: Elevated $CO_2$ and defoliation effects on a shortgrass steppe: Forage quality versus quantity for ruminants. *Agriculture, Ecosystems and Environment*, **111** (1), 166–184. https://doi.org/10.1016/j.agee.2005.06.014

134. Moore, K.J., A.W. Lenssen, and S.L. Fales, 2020: Ch. 39. Factors affecting forage quality. In: *Forages: The Science of Grassland Agriculture*, 7th ed. Moore, K.J., M. Collins, C.J. Nelson, and D.D. Redfearn, Eds. Wiley, 701–717. https://doi.org/10.1002/9781119436669.ch39

135. Klemm, T. and D.D. Briske, 2021: Retrospective assessment of beef cow numbers to climate variability throughout the U.S. Great Plains. *Rangeland Ecology & Management*, **78**, 273–280. https://doi.org/10.1016/j.rama.2019.07.004

136. Haigh, T.R., J.A. Otkin, A. Mucia, M. Hayes, and M.E. Burbach, 2019: Drought early warning and the timing of range managers' drought response. *Advances in Meteorology*, **2019**, 1–14. https://doi.org/10.1155/2019/9461513

137. Derner, J., D. Briske, M. Reeves, T. Brown-Brandl, M. Meehan, D. Blumenthal, W. Travis, D. Augustine, H. Wilmer, D. Scasta, J. Hendrickson, J. Volesky, L. Edwards, and D. Peck, 2018: Vulnerability of grazing and confined livestock in the Northern Great Plains to projected mid- and late-twenty-first century climate. *Climatic Change*, **146** (1–2), 19–42. https://doi.org/10.1007/s10584-017-2029-6

138. Reeves, M.C., M.E. Manning, J.P. DiBenedetto, K.A. Palmquist, W.K. Lauenroth, J.B. Bradford, and D.R. Schlaepfer, 2018: Ch. 6. Effects of climate change on rangeland vegetation in the Northern Rockies. In: *Climate Change and Rocky Mountain Ecosystems*. Halofsky, J.E. and D.L. Peterson, Eds. Springer, Cham, Switzerland, 97–114. https://doi.org/10.1007/978-3-319-56928-4_6

139. Blackfeet Nation, 2022: Blackfeet Nation Agricultural Resource Management Plan. Blackfeet Nation, Browning, MT. https://bnsga.com/governing-documents

140. Olimb, S.K. and B. Robinson, 2019: Grass to grain: Probabilistic modeling of agricultural conversion in the North American Great Plains. *Ecological Indicators*, **102**, 237–245. https://doi.org/10.1016/j.ecolind.2019.02.042

141. Epstein, K., J.H. Haggerty, and H. Gosnell, 2021: With, not for, money: Ranch management trajectories of the super-rich in Greater Yellowstone. *Annals of the American Association of Geographers*, **112** (2), 432–448. https://doi.org/10.1080/24694452.2021.1930512

142. Fairbairn, M., 2020: *Fields of Gold: Financing the Global Land Rush*. Cornell University Press. http://www.jstor.org/stable/10.7591/j.ctvrnfpvf

143. Haggerty, J.H., M. Auger, and K. Epstein, 2018: Ranching sustainability in the Northern Great Plains: An appraisal of local perspectives. *Rangelands*, **40** (3), 83–91. https://doi.org/10.1016/j.rala.2018.03.005

144. Cutter, S.L., B.J. Boruff, and W.L. Shirley, 2003: Social vulnerability to environmental hazards. *Social Science Quarterly*, **84** (2), 242–261. https://doi.org/10.1111/1540-6237.8402002

145. Hjerpe, E., A. Hussain, and T. Holmes, 2020: Amenity migration and public lands: Rise of the protected areas. *Environmental Management*, **66** (1), 56–71. https://doi.org/10.1007/s00267-020-01293-6

146. Powell, L.A., R. Edwards, K.D.J. Powell, and K. Nieland, 2018: Geography of ecotourism potential in the Great Plains: Incentives for conservation. *Great Plains Research*, **28** (1), 15–24. https://doi.org/10.1353/gpr.2018.0001

147. Jedd, T.M., M.J. Hayes, C.M. Carrillo, T. Haigh, C.J. Chizinski, and J. Swigart, 2018: Measuring park visitation vulnerability to climate extremes in U.S. Rockies National Parks tourism. *Tourism Geographies*, **20** (2), 224–249. https://doi.org/10.1080/14616688.2017.1377283

148. Warziniack, T., M. Lawson, and S.K. Dante-Wood, 2018: Ch. 11. Effects of climate change on ecosystem services in the Northern Rockies Region. In: *Climate Change Vulnerability and Adaptation in the Northern Rocky Mountains Part 2*. Halofsky, J.E., D.L. Peterson, S.K.H. Dante-Wood, L. , J.J. Ho, and L.A. Joyce, Eds. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 434–461. https://www.fs.usda.gov/treesearch/pubs/55996

149. Sage, J.L., 2016: Economic Contributions of the Yellowstone River to Park County, Montana. Institute for Tourism and Recreation Research Publications, 346. University of Montana. https://scholarworks.umt.edu/itrr_pubs/346/

150. Hand, M.S. and M. Lawson, 2018: Ch. 9. Effects of climate change on recreation in the Northern Rockies. In: *Climate Change and Rocky Mountain Ecosystems*. Halofsky, J.E. and D.L. Peterson, Eds. Springer, Cham, Switzerland, 169–188. https://doi.org/10.1007/978-3-319-56928-4_9

151. Sage, J.L. and N.P. Nickerson, 2017: The Montana Expression 2017: 2017's Costly Fire Season. Institute for Tourism and Recreation Research, 363. University of Montana. https://scholarworks.umt.edu/itrr_pubs/363

152. Weed, A.S., B.J. Bentz, M.P. Ayres, and T.P. Holmes, 2015: Geographically variable response of *Dendroctonus ponderosae* to winter warming in the western United States. *Landscape Ecology*, **30** (6), 1075–1093. https://doi.org/10.1007/s10980-015-0170-z

153. Wobus, C., E.E. Small, H. Hosterman, D. Mills, J. Stein, M. Rissing, R. Jones, M. Duckworth, R. Hall, M. Kolian, J. Creason, and J. Martinich, 2017: Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environmental Change*, **45**, 1–14. https://doi.org/10.1016/j.gloenvcha.2017.04.006

154. Parthum, B. and P. Christensen, 2022: A market for snow: Modeling winter recreation patterns under current and future climate. *Journal of Environmental Economics and Management*, **113**, 102637. https://doi.org/10.1016/j.jeem.2022.102637

155. Roemer, K.F. and J.H. Haggerty, 2022: The energy transition as fiscal rupture: Public services and resilience pathways in a coal company town. *Energy Research & Social Science*, **91**, 102752. https://doi.org/10.1016/j.erss.2022.102752

156. Haggerty, J.H., M.N. Haggerty, K. Roemer, and J. Rose, 2018: Planning for the local impacts of coal facility closure: Emerging strategies in the U.S. West. *Resources Policy*, **57**, 69–80. https://doi.org/10.1016/j.resourpol.2018.01.010

157. Huang, J. and K.R. Gurney, 2017: Impact of climate change on U.S. building energy demand: Financial implications for consumers and energy suppliers. *Energy and Buildings*, **139**, 747–754. https://doi.org/10.1016/j.enbuild.2017.01.077

158. van Ruijven, B.J., E. De Cian, and I. Sue Wing, 2019: Amplification of future energy demand growth due to climate change. *Nature Communications*, **10** (1), 2762. https://doi.org/10.1038/s41467-019-10399-3

159. Ott, J.P., B.B. Hanberry, M. Khalil, M.W. Paschke, M. Post van der Burg, and A.J. Prenni, 2021: Energy development and production in the Great Plains: Implications and mitigation opportunities. *Rangeland Ecology & Management*, **78**, 257–272. https://doi.org/10.1016/j.rama.2020.05.003

160. Davis, L.W. and C. Hausman, 2022: Who Will Pay for Legacy Utility Costs? NBER Working Paper 28955. National Bureau of Economic Research. https://doi.org/10.3386/w28955

161. Bie, Z., Y. Lin, G. Li, and F. Li, 2017: Battling the extreme: A study on the power system resilience. *Proceedings of the IEEE*, **105** (7), 1253–1266. https://doi.org/10.1109/jproc.2017.2679040

162. Chinowsky, P., J. Helman, S. Gulati, J. Neumann, and J. Martinich, 2019: Impacts of climate change on operation of the US rail network. *Transport Policy*, **75**, 183–191. https://doi.org/10.1016/j.tranpol.2017.05.007

163. EIA, 2022: Annual Energy Outlook 2022. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/outlooks/archive/aeo22/

164. Grubert, E., 2020: Fossil electricity retirement deadlines for a just transition. *Science*, **370** (6521), 1171–1173. https://doi.org/10.1126/science.abe0375

165. Johnson, S. and K. Chau, 2019: Today in Energy: More U.S. coal-fired power plants are decommissioning as retirements continue. U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=40212

166. Schlinger, C., O. Conroy-Ben, C. Cooley, N. Cooley, M. Cruz, D. Dotson, J. Doyle, M.J. Eggers, P. Hardison, M. Hatch, C. Hogue, K. Jacobson Hedin, C. Jones, K. Lanphier, D. Marks-Marino, D. Mosley, F. Olsen Jr., and M. Peacock, 2021: Ch. 4.2. Water. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 98–141. http://nau.edu/stacc2021

167. Righetti, T.K., T. Stoellinger, and R. Godby, 2021: Adapting to coal plant closures: A framework to understand state energy transition resistance. *Environmental Law*, **51** (4), 957–990. https://doi.org/10.13140/rg.2.2.32801.74083

168. Roemer, K.F. and J.H. Haggerty, 2021: Coal communities and the U.S. energy transition: A policy corridors assessment. *Energy Policy*, **151**, 112112. https://doi.org/10.1016/j.enpol.2020.112112

169. Jenkins, J.D., E.N. Mayfield, J. Farbes, R. Jones, N. Patankar, Q. Xu, and G. Schivley, 2022: Preliminary Report: The Climate and Energy Impacts of the Inflation Reduction Act of 2022. REPEAT Project. Princeton University, Princeton, NJ. https://repeatproject.org/docs/repeat_ira_prelminary_report_2022-08-04.pdf

170. EIA, 2022: Electricity Data. U.S. Energy Information Administration. https://www.eia.gov/electricity/data.php

171. Carwile, C., 2021: Race, power, and place: Lakota lessons from Pine Ridge Reservation. *Michigan Journal of Community Service Learning*, **27** (1), 129–153. https://eric.ed.gov/?id=ej1315005

172. Oceti Sakowin Power Authority, 2019: Testimony of Lyle Jack Chairman of the Board of Directors Oceti Sakowin Power Authority. Oceti Sakowin Power Authority, 21 pp. https://democrats-naturalresources.house.gov/download/2-testimony-attachment-ospa-lyle-jack-043019

173. Singletary, L., S. Clow, M. Connolly, D. Marks-Marino, A. Samoy, and S. Stout, 2021: Ch. 6. Economic development. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 174–189. http://nau.edu/stacc2021

174. Wyoming Energy Authority, 2023: WIH2 submits application for DOE funding grant: Western Interstate Hydrogen Hub submits application for U.S. Department of Energy funding grant. Wyoming Energy Authority, Cheyenne, WY, April 10, 2023. https://wyoenergy.org/wih2-application-submitt

175. Vogt, R., C. Burkhart-Kriesel, B. Lubben, L.J. McElravy, T. Meyer, S. Schulz, and J. Weigle, 2020: Severe Weather in Nebraska: Impacts on Nonmetropolitan Nebraskans. Nebraska Rural Poll Research Report 20-1. University of Nebraska, Rural Futures Institute. https://digitalcommons.unl.edu/rfipubs/29/

176. Zambrano, L., C. Cooley, D. Crow Ghost, M. Cruz, P. Hardison, P. Hingst, C. Jones, J. Maldonado, D. Marks-Marino, and S. Tangen, 2021: Ch. 9. Emergency management. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 222–240. http://nau.edu/stacc2021

177. FEMA, 2019: South Dakota Severe Storms, Tornadoes, and Flooding. DR-4469-SD. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/disaster/4469

178. Martin, C., V.W. Simonds, S.L. Young, J. Doyle, M. Lefthand, and M.J. Eggers, 2021: Our relationship to water and experience of water insecurity among Apsáalooke (Crow Indian) people, Montana. *International Journal of Environmental Research and Public Health*, **18** (2), 582. https://doi.org/10.3390/ijerph18020582

179. IHS, 2020: Annual Report to the Congress of the United States on Sanitation Deficiency Levels for Indian Homes and Communities: Fiscal Year 2019. Indian Health Service, Office of Environmental Health and Engineering, Division of Sanitation Facilities Construction, Rockville, MD. https://www.ncbi.nlm.nih.gov/books/nbk571290/

180. Rumbach, A., E. Sullivan, and C. Makarewicz, 2020: Mobile home parks and disasters: Understanding risk to the third housing type in the United States. *Natural Hazards Review*, **21** (2), 05020001. https://doi.org/10.1061/(asce)nh.1527-6996.0000357

181. Paine, M., 2016: Floodplain Management Today: Who Lives in Nebraska Floodplains? Nebraska Department of Natural Resources, 8 pp. https://dnr.nebraska.gov/sites/dnr.nebraska.gov/files/doc/floodplain/newsletters/Floodplain_Management_Today_December_2016.pdf

182. Morris, A.C., 2016: The Challenge of State Reliance on Revenue from Fossil Fuel Production. Climate and Energy Economics Discussion Paper. The Brookings Institution, Washington, DC. https://www.brookings.edu/wp-content/uploads/2016/08/state-fiscal-implications-of-fossil-fuel-production-0809216-morris.pdf

183. NSF, 2022: EPSCoR Criteria for Eligibility. National Science Foundation. https://new.nsf.gov/funding/initiatives/epscor/epscor-criteria-eligibility

184. Van Boven, L. and D.K. Sherman, 2021: Elite influence on public attitudes about climate policy. *Current Opinion in Behavioral Sciences*, **42**, 83–88. https://doi.org/10.1016/j.cobeha.2021.03.023

185. Charnley, S., H. Gosnell, R. Davee, and J. Abrams, 2020: Ranchers and beavers: Understanding the human dimensions of beaver-related stream restoration on western rangelands. *Rangeland Ecology & Management*, **73** (5), 712–723. https://doi.org/10.1016/j.rama.2020.04.008

186. Pfaeffle, T., M.A. Moore, A.E. Cravens, J. McEvoy, and A. Bamzai-Dodson, 2022: Murky waters: Divergent ways scientists, practitioners, and landowners evaluate beaver mimicry. *Ecology and Society*, **27** (1). https://doi.org/10.5751/es-13006-270141

187. NCSE and TFN, 2020: Making the Grade? How State Public School Science Standards Address Climate Change. National Center for Science Education and Texas Freedom Network Education Fund. https://ncse.ngo/files/MakingTheGrade_Final_10.8.2020.pdf

188. Howe, P.D., M. Mildenberger, J.R. Marlon, and A. Leiserowitz, 2015: Geographic variation in opinions on climate change at state and local scales in the USA. *Nature Climate Change*, **5** (6), 596–603. https://doi.org/10.1038/nclimate2583

189. Prokopy, L.S., L.W. Morton, J.G. Arbuckle, A.S. Mase, and A.K. Wilke, 2015: Agricultural stakeholder views on climate change: Implications for conducting research and outreach. *Bulletin of the American Meteorological Society*, **96** (2), 181–190. https://doi.org/10.1175/bams-d-13-00172.1

190. Carley, S., T.P. Evans, M. Graff, and D.M. Konisky, 2018: A framework for evaluating geographic disparities in energy transition vulnerability. *Nature Energy*, **3** (8), 621–627. https://doi.org/10.1038/s41560-018-0142-z

191. Snyder, B.F., 2018: Vulnerability to decarbonization in hydrocarbon-intensive counties in the United States: A just transition to avoid post-industrial decay. *Energy Research & Social Science*, **42**, 34–43. https://doi.org/10.1016/j.erss.2018.03.004

192. Morris, A.C., N. Kaufman, and S. Doshi, 2021: Revenue at risk in coal-reliant counties. *Environmental and Energy Policy and the Economy*, **2**, 83–116. https://doi.org/10.1086/711307

193. Haggerty, J.H., M. Haggerty, and R. Rasker, 2014: Uneven local benefits of renewable energy in the U.S. West: Property tax policy effects. *Western Economics Forum*, **13** (1), 8–22. https://doi.org/10.22004/ag.econ.189734

194. Haggerty, M.N. and J.H. Haggerty, 2021: Ch. 31. Rethinking fiscal policy for inclusive rural development. In: *Investing in Rural Prosperity*. Dumont, A. and D.P. Davis, Eds. Federal Reserve Bank of St. Louis, 447–460. https://www.stlouisfed.org/-/media/project/frbstl/stlouisfed/files/pdfs/community-development/investing-rural/investinginruralprosperity-book.pdf

195. Wen, C., Y. Xu, Y. Kim, and M.E. Warner, 2020: Starving counties, squeezing cities: Tax and expenditure limits in the US. *Journal of Economic Policy Reform*, **23** (2), 101–119. https://doi.org/10.1080/17487870.2018.1509711

196. Haggerty, M., 2021: Innovating fiscal policy to power enduring rural prosperity. In: *Principal Ideas: How Can We Secure Enduring Capital for Equitable Rural Prosperity?* Aspen Institute Community Strategies Group, 4–7. https://www.aspeninstitute.org/publications/principal-ideas/

197. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

198. Zimmerman, M.G. and T.G. Reames, 2021: Where the wind blows: Exploring barriers and opportunities to renewable energy development on United States tribal lands. *Energy Research & Social Science*, **72**, 101874. https://doi.org/10.1016/j.erss.2020.101874

199. The White House, 2021: Fact sheet: The bipartisan infrastructure deal boosts clean energy jobs, strengthens resilience, and advances environmental justice. The White House, Washington, DC, November 8, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/08/fact-sheet-the-bipartisan-infrastructure-deal-boosts-clean-energy-jobs-strengthens-resilience-and-advances-environmental-justice/

200. Look, W., M. Haggerty, and D. Mazzone, 2022: Community Hubs to Support Energy Transition. Issue Brief 22-02. Resources for the Future and Environmental Defense Fund, Washington, DC, 11 pp. https://www.rff.org/publications/issue-briefs/community-hubs-to-support-energy-transition/

201. Smith, K. and P. Hernandez, 2022: Capacity-Limited States Still Struggle to Access FEMA BRIC Grants. Headwaters Economics, Bozeman, MT. https://headwaterseconomics.org/equity/capacity-limited-fema-bric-grants/

202. Hernandez, P., B. Daigle, T. Preston, K. Pohl, K. Smith, B. Powell, and S. Story, 2022: A Rural Capacity Map. Headwaters Economics, Bozeman, MT. https://headwaterseconomics.org/equity/rural-capacity-map/

203. Anderson, S., 2019: *One Size Fits None: A Farm Girl's Search for the Promise of Regenerative Agriculture*. University of Nebraska Press, Lincoln, NE, 312 pp. https://www.nebraskapress.unl.edu/nebraska/9781496205056/

204. Montgomery, D.R., 2017: *Growing a Revolution: Bringing Our Soil Back to Life*. WW Norton & Company, 320 pp. https://wwnorton.com/books/9780393356090

205. Jenkins, J.D., E.N. Mayfield, E.D. Larson, S.W. Pacala, and C. Greig, 2021: Mission net-zero America: The nation-building path to a prosperous, net-zero emissions economy. *Joule*, **5** (11), 2755–2761. https://doi.org/10.1016/j.joule.2021.10.016

206. Trainor, A.M., R.I. McDonald, and J. Fargione, 2016: Energy sprawl is the largest driver of land use change in United States. *PLoS ONE*, **11** (9), e0162269. https://doi.org/10.1371/journal.pone.0162269

207. van Zalk, J. and P. Behrens, 2018: The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, **123**, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023

208. Lark, T.J., 2020: Protecting our prairies: Research and policy actions for conserving America's grasslands. *Land Use Policy*, **97**, 104727. https://doi.org/10.1016/j.landusepol.2020.104727

209. Scholtz, R. and D. Twidwell, 2022: The last continuous grasslands on Earth: Identification and conservation importance. *Conservation Science and Practice*, **4** (3), e626. https://doi.org/10.1111/csp2.626

210. Hise, C., B. Obermeyer, M. Ahlering, J. Wilkinson, and J. Fargione, 2022: Site wind right: Identifying low-impact wind development areas in the central United States. *Land*, **11** (4). https://doi.org/10.3390/land11040462

211. Ginger Paige (Author), November 10, 2020: Oral communication with Anne MacKinnon, University of Wyoming.

212. Lamborn, C.C. and J.W. Smith, 2019: Human perceptions of, and adaptations to, shifting runoff cycles: A case-study of the Yellowstone River (Montana, USA). *Fisheries Research*, **216**, 96–108. https://doi.org/10.1016/j.fishres.2019.04.005.

213. Penmetsa, V. and K.E. Holbert, 2019: Climate change effects on solar, wind and hydro power generation. In: *North American Power Symposium* (NAPS). Wichita, KS, 13–15 October 2019. IEEE. https://doi.org/10.1109/naps46351.2019.9000213

214. Dolan, K.A., P.C. Stoy, and B. Poulter, 2020: Land management and climate change determine second-generation bioenergy potential of the US Northern Great Plains. *GCB Bioenergy*, **12** (7), 491–509. https://doi.org/10.1111/gcbb.12686

215. Hamada, Y., C.R. Zumpf, J.F. Cacho, D. Lee, C.H. Lin, A. Boe, E. Heaton, R. Mitchell, and M.C. Negri, 2021: Remote sensing-based estimation of advanced perennial grass biomass yields for bioenergy. *Land*, **10** (11), 1221. https://doi.org/10.3390/land10111221

216. Peni, D., M.J. Stolarski, A. Bordiean, M. Krzyżaniak, and M. Dębowski, 2020: *Silphium perfoliatum*—A herbaceous crop with increased interest in recent years for multi-purpose use. *Agriculture*, **10** (12), 640. https://doi.org/10.3390/agriculture10120640

217. Zilverberg, C.J., W.C. Johnson, D. Archer, S. Kronberg, T. Schumacher, A. Boe, and C. Novotny, 2014: Profitable prairie restoration: The EcoSun Prairie Farm experiment. *Journal of Soil and Water Conservation*, **69** (1), 22–25. https://doi.org/10.2489/jswc.69.1.22a

218. Stewart, C.E., R.F. Follett, E.G. Pruessner, G.E. Varvel, K.P. Vogel, and R.B. Mitchell, 2015: Nitrogen and harvest effects on soil properties under rainfed switchgrass and no-till corn over 9 years: Implications for soil quality. *GCB Bioenergy*, **7** (2), 288–301. https://doi.org/10.1111/gcbb.12142

219. Stoy, P.C., S. Ahmed, M. Jarchow, B. Rashford, D. Swanson, S. Albeke, G. Bromley, E.N.J. Brookshire, M.D. Dixon, J. Haggerty, P. Miller, B. Peyton, A. Royem, L. Spangler, C. Straub, and B. Poulter, 2018: Opportunities and trade-offs among BECCS and the food, water, energy, biodiversity, and social systems nexus at regional scales. *BioScience*, **68** (2), 100–111. https://doi.org/10.1093/biosci/bix145

220. Oakes, L.E., M.S. Cross, and E.S. Zavaleta, 2021: Rapid assessment to facilitate climate-informed conservation and nature-based solutions. *Conservation Science and Practice*, **3** (8), 472. https://doi.org/10.1111/csp2.472

221. Schipper, E.L.F., 2020: Maladaptation: When adaptation to climate change goes very wrong. *One Earth*, **3** (4), 409–414. https://doi.org/10.1016/j.oneear.2020.09.014

222. Findlater, K., S. Hagerman, R. Kozak, and V. Gukova, 2022: Redefining climate change maladaptation using a values-based approach in forests. *People and Nature*, **4** (1), 231–242. https://doi.org/10.1002/pan3.10278

223. Ojima, D.S., R.T. Conant, W.J. Parton, J.M. Lackett, and T.L. Even, 2021: Recent climate changes across the Great Plains and implications for natural resource management practices. *Rangeland Ecology and Management*, **78**, 180–190. https://doi.org/10.1016/j.rama.2021.03.008

224. Blann, K.L., J.L. Anderson, G.R. Sands, and B. Vondracek, 2009: Effects of agricultural drainage on aquatic ecosystems: A review. *Critical Reviews in Environmental Science and Technology*, **39** (11), 909–1001. https://doi.org/10.1080/10643380801977966

225. Yang, Y., M. Anderson, F. Gao, C. Hain, W. Kustas, T. Meyers, W. Crow, R. Finocchiaro, J. Otkin, L. Sun, and Y. Yang, 2017: Impact of tile drainage on evapotranspiration in South Dakota, USA, based on high spatiotemporal resolution evapotranspiration time series from a multisatellite data fusion system. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **10** (6), 2550–2564. https://doi.org/10.1109/jstars.2017.2680411

226. Werner, B., J. Tracy, W.C. Johnson, R.A. Voldseth, G.R. Guntenspergen, and B. Millett, 2016: Modeling the effects of tile drain placement on the hydrologic function of farmed prairie wetlands. *JAWRA Journal of the American Water Resources Association*, **52** (6), 1482–1492. https://doi.org/10.1111/1752-1688.12471

227. Finocchiaro, R.G. 2014: Agricultural Subsurface Drainage Tile Locations by Permits in South Dakota. U.S. Geological Survey Data Release. https://doi.org/10.5066/f7ks6pnw

228. Finocchiaro, R.G. 2016: Agricultural Subsurface Drainage Tile Locations by Permits in North Dakota. U.S. Geological Survey Data Release. https://doi.org/10.5066/f7qf8qzw

229. Sando, T., 2015: Trends in North Dakota field water management. *The Oxbow - North Dakota State Water Commission*, April 2015. https://www.swc.nd.gov/info_edu/reports_and_publications/oxbow_articles/2015_april.pdf

230. Tangen, B. and M.T. Wiltermuth, 2018: Prairie Pothole Region wetlands and subsurface drainage systems: Key factors for determining drainage setback distances. *Journal of Fish and Wildlife Management*, **9** (1), 274–284. https://doi.org/10.3996/092017-jfwm-076

231. Dahl, T.E., 2014: Status and Trends of Prairie Wetlands in the United States 1997 to 2009. U.S. Department of the Interior, Fish and Wildlife Service, Ecological Services, Washington, DC, 67 pp. https://www.fws.gov/wetlands/documents/Status-and-Trends-of-Prairie-Wetlands-in-the-United-States-1997-to-2009.pdf

232. Mushet, D.M., M.B. Goldhaber, C.T. Mills, K.I. McLean, V.M. Aparicio, R.B. McCleskey, J.M. Holloway, and C.A. Stockwell, 2015: Chemical and Biotic Characteristics of Prairie Lakes and Large Wetlands in South-Central North Dakota—Effects of a Changing Climate. Scientific Investigations Report 2015–5126. U.S. Geological Survey, Reston, VA, 55 pp. https://doi.org/10.3133/sir20155126

233. McCauley, L.A., M.J. Anteau, M.P. van der Burg, and M.T. Wiltermuth, 2015: Land use and wetland drainage affect water levels and dynamics of remaining wetlands. *Ecosphere*, **6** (6), 92. https://doi.org/10.1890/es14-00494.1

234. McKenna, O.P., S.R. Kucia, D.M. Mushet, M.J. Anteau, and M.T. Wiltermuth, 2019: Synergistic interaction of climate and land-use drivers alter the function of North American, prairie-pothole wetlands. *Sustainability*, **11** (23), 6581. https://doi.org/10.3390/su11236581

235. Schottler, S.P., J. Ulrich, P. Belmont, R. Moore, J.W. Lauer, D.R. Engstrom, and J.E. Almendinger, 2014: Twentieth century agricultural drainage creates more erosive rivers. *Hydrological Processes*, **28** (4), 1951–1961. https://doi.org/10.1002/hyp.9738

236. King, K.W., M.R. Williams, M.L. Macrae, N.R. Fausey, J. Frankenberger, D.R. Smith, P.J.A. Kleinman, and L.C. Brown, 2015: Phosphorus transport in agricultural subsurface drainage: A review. *Journal of Environmental Quality*, **44** (2), 467–485. https://doi.org/10.2134/jeq2014.04.0163

237. Speir, S.L., J.L. Tank, M. Bieroza, U.H. Mahl, and T.V. Royer, 2021: Storm size and hydrologic modification influence nitrate mobilization and transport in agricultural watersheds. *Biogeochemistry*, **156** (3), 319–334. https://doi.org/10.1007/s10533-021-00847-y

238. Cheng, F.Y., K.J. Van Meter, D.K. Byrnes, and N.B. Basu, 2020: Maximizing US nitrate removal through wetland protection and restoration. *Nature*, **588** (7839), 625–630. https://doi.org/10.1038/s41586-020-03042-5

239. Doherty, K.E., D.W. Howerter, J.H. Devries, and J. Walker, 2018: Prairie Pothole Region of North America. In: *The Wetland Book: II: Distribution, Description, and Conservation*. Finlayson, C.M., G.R. Milton, R.C. Prentice, and N.C. Davidson, Eds. Springer, Dordrecht, Netherlands, 679–688. https://doi.org/10.1007/978-94-007-4001-3_15

240. Johnson, W.C. and G.R. Guntenspergen, 2022: Ch. 10. Maintaining wetland ecosystem services in a changing climate. In: *Soil Hydrology in a Changing Climate*. Blanco, H., S. Kumar, and S. Anderson, Eds. CSIRO Publishing, 32. https://www.publish.csiro.au/book/7978/

241. Mitchell, M.E., S.D. Shifflett, T. Newcomer-Johnson, A. Hodaj, W. Crumpton, J. Christensen, B. Dyson, T.J. Canfield, S. Richmond, M. Helmers, D. Lemke, M. Lechtenberg, C. Taylor, and K.J. Forshay, 2022: Ecosystem services in Iowa agricultural catchments: Hypotheses for scenarios with water quality wetlands and improved tile drainage. *Journal of Soil and Water Conservation*, **77** (4), 426–440. https://doi.org/10.2489/jswc.2022.00127

242. Keeler, J., 2019: Yankton Sioux: 'Our community is literally drowning'. *Indian Country Today*, October 1, 2019. https://www.indianz.com/news/2019/10/01/yankton-sioux-our-community-is-literally.asp

243. Johnson, W.C. and D.H. Knight, 2022: *Ecology of the Dakotas: Past, Present, and Future*. Yale University Press, New Haven, CT, 336 pp. https://yalebooks.yale.edu/book/9780300253818/ecology-of-dakota-landscapes/

244. Basche, A., K. Tully, N.L. Álvarez-Berríos, J. Reyes, L. Lengnick, T. Brown, J.M. Moore, R.E. Schattman, L.K. Johnson, and G. Roesch-McNally, 2020: Evaluating the untapped potential of US conservation investments to improve soil and environmental health. *Frontiers in Sustainable Food Systems*, **4**, 547876. https://doi.org/10.3389/fsufs.2020.547876

245. Brown, G., 2018: *Dirt to Soil: One Family's Journey into Regenerative Agriculture*. Chelsea Green Publishing, 240 pp. https://www.chelseagreen.com/product/dirt-to-soil/

246. Smart, A.J., D. Redfearn, R. Mitchell, T. Wang, C. Zilverberg, P.J. Bauman, J.D. Derner, J. Walker, and C. Wright, 2021: Forum: Integration of crop-livestock systems: An opportunity to protect grasslands from conversion to cropland in the US Great Plains. *Rangeland Ecology and Management*, **78**, 250–256. https://doi.org/10.1016/j.rama.2019.12.007

247. Zilverberg, C.J., K. Heimerl, T.E. Schumacher, D.D. Malo, J.A. Schumacher, and W.C. Johnson, 2018: Landscape dependent changes in soil properties due to long-term cultivation and subsequent conversion to native grass agriculture. *CATENA*, **160**, 282–297. https://doi.org/10.1016/j.catena.2017.09.020

248. Fenster, T.L.D., C.E. LaCanne, J.R. Pecenka, R.B. Schmid, M.M. Bredeson, K.M. Busenitz, A.M. Michels, K.D. Welch, and J.G. Lundgren, 2021: Defining and validating regenerative farm systems using a composite of ranked agricultural practices. *F1000Research*, **10**, 115. https://doi.org/10.12688/f1000research.28450.1

249. Krupek, F.S., D. Redfearn, K.M. Eskridge, and A. Basche, 2022: Ecological intensification with soil health practices demonstrates positive impacts on multiple soil properties: A large-scale farmer-led experiment. *Geoderma*, **409**, 115594. https://doi.org/10.1016/j.geoderma.2021.115594

250. LaCanne, C.E. and J.G. Lundgren, 2018: Regenerative agriculture: Merging farming and natural resource conservation profitably. *PeerJ*, **6**, 4428. https://doi.org/10.7717/peerj.4428

251. Rosenzweig, S.T., S.J. Fonte, and M.E. Schipanski, 2018: Intensifying rotations increases soil carbon, fungi, and aggregation in semi-arid agroecosystems. *Agriculture, Ecosystems & Environment*, **258**, 14–22. https://doi.org/10.1016/j.agee.2018.01.016

252. Rosenzweig, S.T., M.E. Stromberger, and M.E. Schipanski, 2018: Intensified dryland crop rotations support greater grain production with fewer inputs. *Agriculture, Ecosystems & Environment*, **264**, 63–72. https://doi.org/10.1016/j.agee.2018.05.017

253. Rosenzweig, S.T., M.S. Carolan, and M.E. Schipanski, 2020: A dryland cropping revolution? Linking an emerging soil health paradigm with shifting social fields among wheat growers of the High Plains. *Rural Sociology*, **85** (2), 545–574. https://doi.org/10.1111/ruso.12304

254. Wick, A.F., J. Haley, C. Gasch, T. Wehlander, L. Briese, and S. Samson-Liebig, 2019: Network-based approaches for soil health research and extension programming in North Dakota, USA. *Soil Use and Management*, **35** (1), 177–184. https://doi.org/10.1111/sum.12444

255. Wang, T., H. Jin, U. Kreuter, and R. Teague, 2021: Expanding grass-based agriculture on marginal land in the U.S. Great Plains: The role of management intensive grazing. *Land Use Policy*, **104**, 105155. https://doi.org/10.1016/j.landusepol.2020.105155

256. Craig, R.K., 2020: Water law and climate change in the United States: A review of the legal scholarship. *WIREs Water*, **7** (3), e1423. https://doi.org/10.1002/wat2.1423

257. Ginger Paige (Author), August 25, 2022: Oral communication with Joseph Cook, Irrigation Science and Management Center, University of Wyoming.

258. Ginger Paige (Author), April 4, 2023: Email communication with Kelsey Peck, Popo Agie Conservation District, Lander, WY.

259. Cosens, B. and B. Chaffin, 2016: Adaptive governance of water resources shared with Indigenous Peoples: The role of law. *Water*, **8** (3), 97. https://doi.org/10.3390/w8030097

260. Rinella, M.J., S.E. Bellows, T.W. Geary, R.C. Waterman, L.T. Vermeire, K.O. Reinhart, M.L. Van Emon, and L.A. Cook, 2022: Early calving benefits livestock production under winter and spring warming. *Rangeland Ecology & Management*, **81**, 63–68. https://doi.org/10.1016/j.rama.2022.01.003

261. Haigh, T.R., M. Hayes, J. Smyth, L. Prokopy, C. Francis, and M. Burbach, 2021: Ranchers' use of drought contingency plans in protective action decision making. *Rangeland Ecology and Management*, **74**, 50–62. https://doi.org/10.1016/j.rama.2020.09.007

262. Lassa, M.J., H. Wilmer, M. Boone, Z. Brown, J.D. Derner, D.E. Peck, C. Thissen, and C. Marlow, 2020: How to talk with ranchers about drought and climate resilience: Lessons from knowledge exchange workshops in Montana. *Journal of Extension*, **58** (5), 18. https://www.fs.usda.gov/treesearch/pubs/61765

263. Smart, A.J., K. Harmoney, J.D. Scasta, M.B. Stephenson, J.D. Volesky, L.T. Vermeire, J.C. Mosley, K. Sedivec, M. Meehan, T. Haigh, J.D. Derner, and M.P. McClaran, 2021: Forum: Critical decision dates for drought management in central and northern Great Plains rangelands. *Rangeland Ecology & Management*, **78**, 191–200. https://doi.org/10.1016/j.rama.2019.09.005

264. Wilmer, H., D.J. Augustine, J.D. Derner, M.E. Fernández-Giménez, D.D. Briske, L.M. Roche, K.W. Tate, and K.E. Miller, 2018: Diverse management strategies produce similar ecological outcomes on ranches in western Great Plains: Social-ecological assessment. *Rangeland Ecology & Management*, **71** (5), 626–636. https://doi.org/10.1016/j.rama.2017.08.001

265. Hillenbrand, M.R., F. Thompson, S. Wang, S. Apfelbaum, and R. Teague, 2019: Impacts of holistic planned grazing with bison compared to continuous grazing with cattle in South Dakota shortgrass prairie. *Agriculture, Ecosystems & Environment*, **279**, 156–168. https://doi.org/10.1016/j.agee.2019.02.005

266. Smith, A.P., L. Yung, A.J. Snitker, R.K. Bocinsky, E.C. Metcalf, and K. Jencso, 2021: Scalar mismatches and underlying factors for underutilization of climate information: Perspectives from farmers and ranchers. *Frontiers in Climate*, **3**, 663071. https://doi.org/10.3389/fclim.2021.663071

267. Peck, D., J. Derner, W. Parton, M. Hartman, and B. Fuchs, 2019: Flexible stocking with Grass-Cast: A new grassland productivity forecast to translate climate outlooks for ranchers. *Western Economics Forum*, **17** (1), 24–39. https://doi.org/10.22004/ag.econ.287342

268. *Water Resources Development Act* 2020, 2020: 116th Congress. H.R. 7575. https://www.congress.gov/bill/116th-congress/house-bill/7575/text

269. Spinrad, R., 2021: Statement from NOAA Administrator Rick Spinrad on the signing of the bipartisan Infrastructure Investment and Jobs Act. National Oceanic and Atmospheric Administration, November 15, 2021. https://www.noaa.gov/news-release/statement-from-noaa-administrator-rick-spinrad-on-signing-of-bipartisan-infrastructure-investment

270. Smith, K. and A. Savitt, 2020: Implementing watershed-scale flood mitigation projects Grand Island, Nebraska. In: *Building for the Future: Five Midwestern Communities Reduce Flood Risk*. Headwaters Economics, 15–18. https://headwaterseconomics.org/wp-content/uploads/FloodCaseStudies_LowRes.pdf

271. Blackfeet Nation, 2018: Blackfeet Climate Change Adaptation Plan. Blackfeet Nation. https://bcapwebsite.files.wordpress.com/2018/04/bcap_final_4-11.pdf

272. CSKT, 2016: Climate Change Strategic Plan. Confederated Salish and Kootenai Tribes of the Flathead Reservation. http://csktclimate.org/index.php/resources/resources

273. Sicangu Climate Crisis Working Group, 2022: A Climate Adaptation Plan for the Sicangu Lakota Oyate. Rosebud Sioux Tribe. https://www.rosebudsiouxtribe-nsn.gov/_files/ugd/ed1fef_53c3d954c1ef4c9d8d8ce441f58cb55c.pdf

274. Flandreau Santee Sioux Tribe and Great Plains Tribal Water Alliance, 2020: Flandreau Santee Sioux Tribe Drought Adaptation Plan. Flandreau Santee Sioux Tribe. https://www.tribalwateralliance.org/drought-adaptation-plans

275. Oglala Sioux Tribe and Great Plains Tribal Water Alliance, 2020: Oglala Sioux Tribe Drought Adaptation Plan. Oglala Sioux Tribe. https://www.tribalwateralliance.org/drought-adaptation-plans

276. Rosebud Sioux Tribe and Great Plains Tribal Water Alliance, 2020: Rosebud Sioux Tribe Drought Adaptation Plan. Rosebud Sioux Tribe. https://www.tribalwateralliance.org/drought-adaptation-plans

277. Standing Rock Sioux Tribe and Great Plains Tribal Water Alliance, 2020: Standing Rock Sioux Tribe Drought Adaptation Plan. Standing Rock Sioux Tribe. https://www.tribalwateralliance.org/drought-adaptation-plans

278. Pomerville, A., A. Kawennison Fetter, and J.P. Gone, 2022: American Indian behavioral health treatment preferences as perceived by Urban Indian Health Program providers. *Qualitative Health Research*, **32** (3), 465–478. https://doi.org/10.1177/10497323211057857

279. Stefan Tangen (Author), May 12, 2022: Oral communication with P. Antoine, Sicangu Lakota Treaty Council.

280. Stefan Tangen (Author), April 27, 2022: Oral communication with P. Two Eagle, Sicangu Lakota Treaty Council.

281. DOI, 2022: Secretary Haaland takes action to restore tribal authority to adopt water laws. U.S. Department of the Interior, Washington, DC, April 7, 2022. https://www.doi.gov/pressreleases/secretary-haaland-takes-action-restore-tribal-authority-adopt-water-laws

282. Levitus, J., 2019: The Ksik Stakii Project Beaver Mimicry Guidebook: A Guide to Natural Water Storage in Blackfeet Nation. Blackfeet Nation. https://bcapwebsite.files.wordpress.com/2019/12/beaver-mimicry-guidebook.pdf

283. Miller, B.W., G.W. Schuurman, A.J. Symstad, A.N. Runyon, and B.C. Robb, 2022: Conservation under uncertainty: Innovations in participatory climate change scenario planning from U.S. national parks. *Conservation Science and Practice*, **4** (3), 12633. https://doi.org/10.1111/csp2.12633

284. Runyon, A.N., A.R. Carlson, J. Gross, D.J. Lawrence, and G.W. Schuurman, 2020: Repeatable approaches to work with scientific uncertainty and advance climate change adaptation in US national parks. *Parks Stewardship Forum*, **36** (1), 98–104. https://doi.org/10.5070/p536146402

285. Fisichelli, N.A., G. Schuurman, A.J. Symstad, A. Ray, J.M. Friedman, B. Miller, and E. Rowland, 2016: Resource Management and Operations in Central North Dakota: Climate Change Scenario Planning Workshop Summary November 12–13, 2015, Bismarck, ND. Natural Resource Report NPS/NRSS/NRR--2016/1262. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://pubs.er.usgs.gov/publication/70176346

286. Fisichelli, N.A., G.W. Schuurman, A.J. Symstad, A. Ray, B. Miller, M. Cross, and E. Rowland, 2016: Resource Management and Operations in Southwest South Dakota: Climate Change Scenario Planning Workshop Summary January 20–21, 2016, Rapid City, SD. Natural Resource Report NPS/NRSS/NRR—2016/1289. U.S. Department of the Interior, National Park Service, Fort Collins, CO. http://pubs.er.usgs.gov/publication/70176347

287. Miller, B., A. Symstad, and G.W. Schuurman, 2019: Implications of Climate Scenarios for Badlands National Park Resource Management. U.S. Geological Survey and the National Park Service, 5 pp. https://www.nps.gov/subjects/climatechange/upload/2019-03-26badlclimatescenariosbrief_508compliant.pdf

288. Miller, B., A.J. Symstad, L. Frid, N.A. Fisichelli, and G.W. Schuurman, 2017: Co-producing simulation models to inform resource management: A case study from southwest South Dakota. *Ecosphere*, **8** (12), 02020. https://doi.org/10.1002/ecs2.2020

289. Runyon, A.N., G.W. Schuurman, B.W. Miller, A.J. Symstad, and A.R. Hardy, 2021: Climate Change Scenario Planning for Resource Stewardship at Wind Cave National Park: Climate Change Scenario Planning Summary. Natural Resource Report, NPS/NRSS/NRR—2021/2274. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://doi.org/10.36967/nrr-2286672

290. Schuurman, G.W., A. Symstad, B.W. Miller, A. Runyon, and R. Ohms, 2019: Climate Change Scenario Planning for Resource Stewardship: Applying a Novel Approach in Devils Tower National Monument. Natural Resource Report NPS/NRSS/CCRP/NRR—2019/2052. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://irma.nps.gov/datastore/downloadfile/632857

291. Symstad, A.J., N.A. Fisichelli, B.W. Miller, E. Rowland, and G.W. Schuurman, 2017: Multiple methods for multiple futures: Integrating qualitative scenario planning and quantitative simulation modeling for natural resource decision making. *Climate Risk Management*, **17**, 78–91. https://doi.org/10.1016/j.crm.2017.07.002

292. Lawrence, D.J., A.N. Runyon, J.E. Gross, G.W. Schuurman, and B.W. Miller, 2021: Divergent, plausible, and relevant climate futures for near- and long-term resource planning. *Climatic Change*, **167** (3), 1–20. https://doi.org/10.1007/s10584-021-03169-y

293. Vicente-Serrano, S.M., S. Beguería, and J.I. López-Moreno, 2010: A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration Index. *Journal of Climate*, **23** (7), 1696–1718. https://doi.org/10.1175/2009jcli2909.1

294. Schuurman, G.W., B.W. Miller, A.J. Symstad, A.N. Runyon, and B.C. Robb, 2022: Overcoming "Analysis Paralysis" through Better Climate Change Scenario Planning. *Park Science*, **36** (1). https://www.nps.gov/articles/000/overcoming-analysis-paralysis-through-better-climate-change-scenario-planning.htm

295. National Academies of Sciences, Engineering, and Medicine, 2021: *Accelerating Decarbonization of the U.S. Energy System*. The National Academies Press, Washington, DC, 268 pp. https://doi.org/10.17226/25932

296. Pipa, A.F. and N. Geismar, 2020: Reimagining Rural Policy: Organizing Federal Assistance to Maximize Rural Prosperity. The Brookings Institution, 37 pp. https://www.brookings.edu/wp-content/uploads/2020/11/rural-dev-assistance-brief.pdf

297. Fan, Q., K. Fisher-Vanden, and H.A. Klaiber, 2018: Climate change, migration, and regional economic impacts in the United States. *Journal of the Association of Environmental and Resource Economists*, **5** (3), 643–671. https://doi.org/10.1086/697168

298. Xu, C., T.A. Kohler, T.M. Lenton, J.C. Svenning, and M. Scheffer, 2020: Future of the human climate niche. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (21), 11350–11355. https://doi.org/10.1073/pnas.1910114117

299. Hoerling, M., J. Eischeid, and R. Webb, 2013: Climate Assessment Report: Understanding and Explaining Climate Extremes in the Missouri River Basin Associated with the 2011 Flooding. National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Earth System Research Laboratory, Boulder, CO. https://www.esrl.noaa.gov/psd/csi/factsheets/pdf/noaa-mrb-climate-assessment-report.pdf

300. Allen, J.T., 2017: Hail potential heating up. *Nature Climate Change*, **7** (7), 474–475. https://doi.org/10.1038/nclimate3327

301. Lancet Countdown, 2021: 2021 Lancet Countdown on Health and Climate Change: Policy Brief for the United States of America. Salas, R.N., P.K. Lester, and J.J. Hess, Eds. Lancet Countdown, London, UK. https://www.lancetcountdownus.org/2021-lancet-countdown-us-brief/

Fifth National Climate Assessment: Chapter 26

# Southern Great Plains

# Chapter 26. Southern Great Plains

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# Introduction

Residents and visitors in the Southern Great Plains—Kansas, Oklahoma, and Texas—benefit from the region's working coasts, sandy beaches, southern forests, grasslands, urban areas, rural towns, scrublands, rangelands, and croplands. The region spans 20 ecoregions,[1] each with distinct and diverse species of plants and animals. Those ecosystems provide clean air and water, healthy soils, landscapes for recreation and tourism, habitats for wild plants and animals, and other benefits.[2] The region's 47 Federally Recognized Tribes were forcibly relocated to the region from elsewhere or constricted to fragments of their traditional homelands (circa 1830–1890).[3] Contemporary immigrants from many countries have joined generations of Indigenous Peoples and those who trace their roots to Mexico, Europe, and Africa.[4] The region's distinct peoples and ecosystems experience the impacts of climate change differently, requiring unique responses to climate risk and resources for resilience.

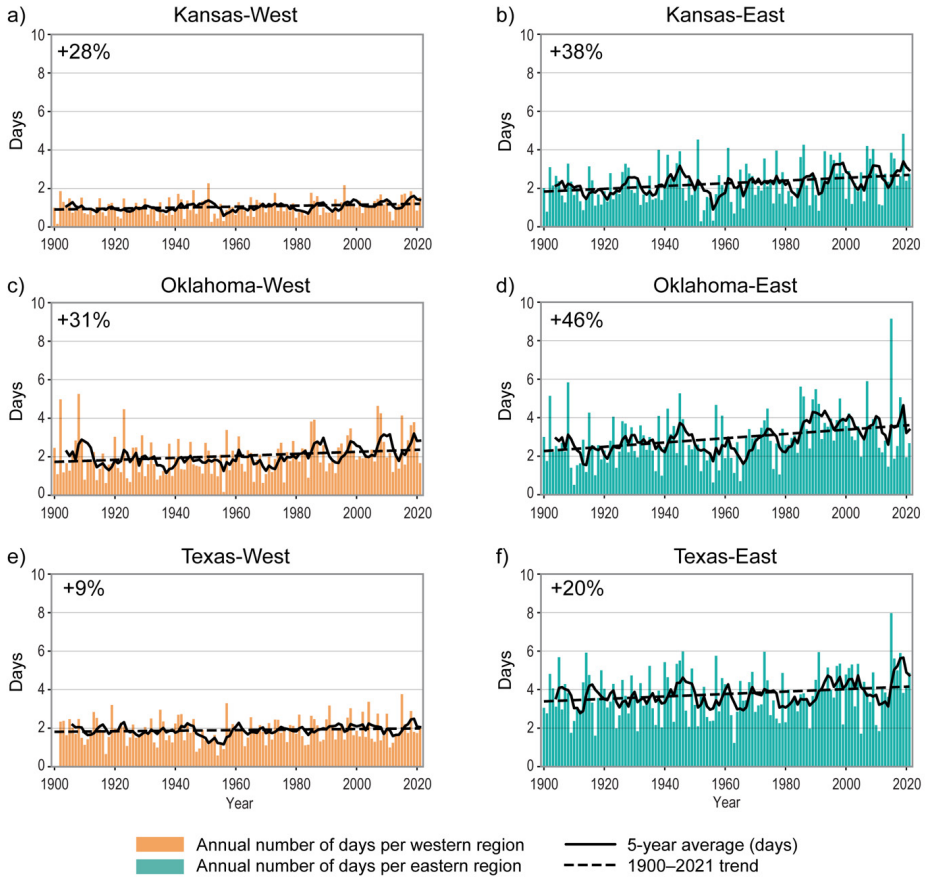
Water is unevenly available across the Southern Great Plains, contributing to distinct lifestyles, workforces, and social burdens. Annual precipitation amounts are lowest in the western portion of the region (10–15 inches) and increase substantially near the eastern boundary (over 50 inches), with high annual and seasonal precipitation variability everywhere.[4] Rivers generally flow from northwest to southeast, and shallow transient wetlands dot western landscapes. These surface waters are critical to sustain irrigation, livestock, and ecological diversity.[5,6] Groundwater is essential near and west of Interstate 35, with aquifers primarily supporting agricultural production and public water supply.[7] Although governments have created reservoirs for flood control, drinking water, irrigation, and recreation,[8] the region experiences some of the country's worst water shortages, and these are projected to increase in both intensity and duration.[9]

Energy is a dominant driver of the region's economy. The vast reserves of fossil fuels in the region have supported economic development nationwide and worldwide.[10] In the past two decades, wind and solar energy generation has proliferated across western lands. In 2021 Texas, Oklahoma, and Kansas ranked first (34,400 megawatts [MW] of installed capacity), third (10,400 MW), and fourth (8,300 MW), respectively, in the Nation in wind energy generation.[11] The reliability of renewable and nonrenewable energy generation and distribution is challenged by tropical storms, wildfire, heat, winter storms, flooding, and drought (KM 5.1).

The region encompasses some of the Nation's fastest-growing cities as well as many small rural communities with declining populations. Rural communities support much of the region's food, fiber, and energy production, in addition to recreational activities. The region's metropolitan areas are leaders in finance, research and development, service and energy industries, medical care, and tourism. Climate extremes and their impacts have harmed all communities, damaging infrastructure and agricultural production, disrupting commerce and price stability, and amplifying social inequities (KMs 11.1, 11.3, 12.2).

Although climate change is global (KM 3.1), its specific impacts are regional (KM 3.3). Thus far, the Southern Great Plains has seen fewer direct, large-scale impacts of climate change than other regions because of its relatively low latitude, flat terrain, and high natural climate variability. Even so, annual average temperatures have increased from 1900 to 2020: 1.5°F for Texas and Kansas[12,13] and 0.6°F for Oklahoma.[14] Annual precipitation has increased across most of the region except far west Texas (Figure 2.4). In addition, days with 2 or more inches of precipitation have become more frequent across the Southern Great Plains, with larger increases in the eastern half of the region than the western half (Figure 26.1).[15] Between 2000 and 2021, Texas endured its five wettest months on record, as well as 19 named tropical storms;[13] 8 of these storms were hurricanes, including Harvey (2017), Ike (2008), and Rita (2005). In contrast, over one-quarter of Kansas experienced severe to exceptional drought during 56 of the 156 months from 2010 to 2022. During this period, Oklahoma and Texas experienced 69 and 82 months, respectively, of these severe to exceptional drought conditions.[16] Between 2018 and 2022 NOAA reported 52 individual billion-dollar climate-related disasters affecting all or part of the region.[17]

## Annual Number of Days with Precipitation of 2 Inches or More (1900–2021)




**The frequency of days with precipitation of 2 inches or more has increased across the Southern Great Plains.**

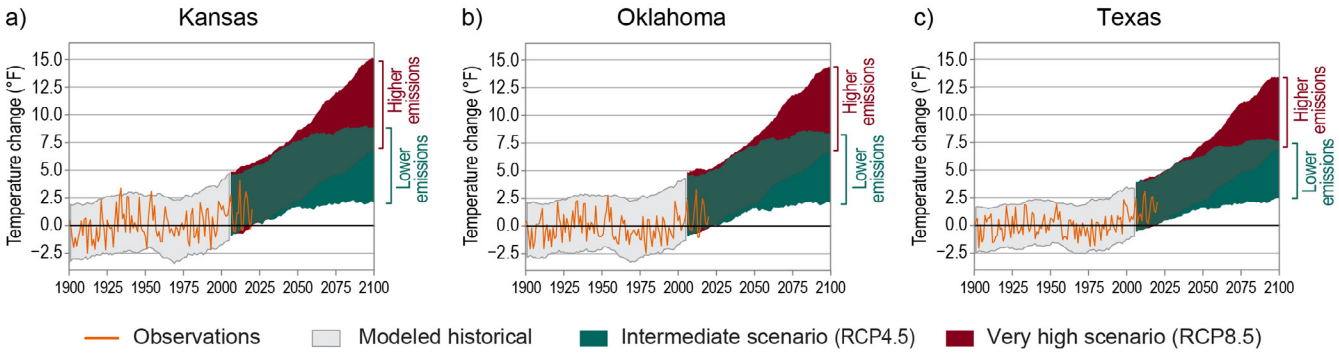
**Figure 26.1.** These graphs show the annual number of days (colored bars) with daily precipitation of 2 inches or more from 1900 to 2021 in (**a**) western Kansas (28% increase for the long-term, linear trend), (**b**) eastern Kansas (38% increase), (**c**) western Oklahoma (31% increase), (**d**) eastern Oklahoma (46% increase), (**e**) western Texas (9% increase), and (**f**) eastern Texas (20% increase). (Station data were unavailable for 1900 and 1901 in western Texas.) Solid black lines show five-year averages; dashed black lines denote the 1900–2021 trend. The number of days has been highly variable from year to year, with fewer 2-inch events in the west (gold bars) on average than in the east (green bars; divided at 97.5° west, near Wichita, Oklahoma City, Fort Worth, and Corpus Christi). Days with precipitation of 2 inches or more have increased in all six regions. Figure credit: NOAA NCEI and CISESS NC.

Since the Fourth National Climate Assessment in 2018, there has been substantial growth in utility-scale electricity generation from wind energy across the region and from solar energy in Texas. At the same time, there has been a significant decrease in the use of coal for electricity in Oklahoma and Texas,[18] although Texas's greenhouse gas emissions still far exceed those of any other US state.[19] The February 2021 cold outbreak and the COVID-19 pandemic highlighted the fragility of the energy and healthcare systems to large-scale stressors. Many of the largest cities in the Southern Great Plains have released climate resilience or sustainability plans since 2018. As research has grown on the disproportionate impacts of climate change on overburdened populations, these cities also have started incorporating social justice concepts into their planning processes.

Future temperatures are expected to be historically unprecedented in the instrumental record in all three states (Figure 26.2). By midcentury, annual average temperatures are projected to exceed historical record levels regardless of emissions pathway. In addition, the number of extremely hot days and the intensity of drought conditions are projected to increase, and the number of extremely cold days is expected to

decrease (KM 2.2). In general, southwestern and southern areas of the Southern Great Plains are projected to become drier, and northeastern areas are expected to become wetter (Figure 2.10). The changes in timing, intensity, and frequency of certain climate conditions and extreme events are expected to influence how we—the residents of the Southern Great Plains—live with family and friends (KM 26.1), work in business and industry (KM 26.2), play sports and enjoy leisure activities (KM 26.3), heal existing environmental inequities and injustices (KM 26.4), and serve residents through public infrastructure and services (KM 26.5).

### Historical and Projected Changes in Air Temperature (1900–2100)




**Air temperatures for Kansas, Oklahoma, and Texas are projected to be historically unprecedented by the end of the century.**

**Figure 26.2.** These graphs show observed and projected changes (compared to the 1901–1960 average; thick black line) in near-surface air temperature for (**a**) Kansas, (**b**) Oklahoma, and (**c**) Texas. Annual average temperature observations (orange line) are plotted with the range of temperatures from climate model output (light gray shading) for the historical period. The overlap of observed and modeled temperatures indicates that the models represent the region's climate reasonably well. Climate projections out to 2100 use an intermediate scenario (RCP4.5; green shading) and a very high scenario (RCP8.5; red shading), showing a range of possible future temperatures. Results from both scenarios indicate substantial warming in Kansas, Oklahoma, and Texas by midcentury and historically unprecedented warming by the end of the century. (a, b) Adapted from Frankson et al. 2022[12] and Frankson et al. 2022;[14] (c) adapted from Runkle et al. 2022.[13]

## Key Message 26.1

## How We Live: Climate Change Is Degrading Lands, Waters, Culture, and Health

Climate change is beginning to alter how we live in the Southern Great Plains, putting us at risk from climate hazards that degrade our lands and waters, quality of life, health and well-being, and cultural interconnectedness (*high confidence*). Many climate hazards are expected to become more frequent, intense, or prolonged; to broaden in spatial extent; and to result in more people experiencing costly, deadly, or stressful climate-related conditions (*very likely*, *high confidence*). To address the growing risk, effective climate-resilient actions include implementing nature-based solutions; valuing Indigenous, traditional, and local knowledges; and infusing climate change solutions into community planning (*medium confidence*).

Lands and waters of the Southern Great Plains are important to people's ways of life, shaping the stories of family and community successes and struggles. Climate change has added stress to lands and waters that already contend with invasive species, land-use change, and land fragmentation (KM 8.2).[20] Rangeland and grassland health is being degraded by woody plant encroachment from precipitation changes[21] or fire suppression.[22] Wetlands are suffering from high evaporation rates or excess nutrient inputs from flood runoff.[23] Ice storms, drought, and high temperatures have stressed forests, making them susceptible to post-event trauma (e.g., disease, pests, fire) and mortality.[24,25,26]

Urban landscapes are being harmed by air and water pollution, extreme heat, drought, and flooding (KM 12.2). As climate change brings heavier rainfall, cities and towns are increasingly at risk of high-impact floods. The extensive impervious surfaces (e.g., parking lots, roofs) of metropolitan areas such as Houston (Box 26.1) increase the likelihood of widespread flooding because of increased runoff.[27] Coastal cities have added risk from sea level rise. By 2100, under a projected 3.3 feet of sea level rise along the Texas Gulf Coast, a Category 2 hurricane is estimated to cause 3–10 times more damage to buildings and be $10.4 billion (in 2022 dollars) more costly (from averages of $3.7 to $14.1 billion) than a similar storm today.[28]

Traditions, heritage, and culture related to land and water are also at risk because of changes forced by novel climatic conditions.[29,30] Warming temperatures are shifting ranges of culturally significant species, making them absent or rare on lands where Indigenous People have access.[31] Heavy rainfall and resulting flooding have inundated archaeological sites.[32] Large-scale or repetitive damages from sea level rise, tropical cyclones, drought, and flooding have increased displacement of people and migration at the Texas–Mexico border and from coastal communities (KM 9.3).[33,34,35,36]

Tribes are revitalizing their cultural practices and relationships with nature to find solutions that resonate with their traditions (KMs 16.2, 16.3). For example, the Tribal Alliance for Pollinators is building on Indigenous cultural and medicinal traditions to preserve and restore grassland ecosystems for monarch butterflies and other threatened pollinators.[31] To reduce harmful algal blooms that proliferate with hot temperatures,[37] the Chickasaw Nation has teamed with local landowners and agriculture producers in southern Oklahoma to remove invasive junipers, improve fertilizer application methods, and restore native habitats for ground-nesting birds.[38]

## Box 26.1. Place Matters: A Case Study of Houston, Texas

Adaptation and mitigation actions occur at the local level, where people's values and the neighboring landscape matter. Houston, Texas, illustrates how urban communities are starting to incorporate climate-smart actions into their planning efforts.

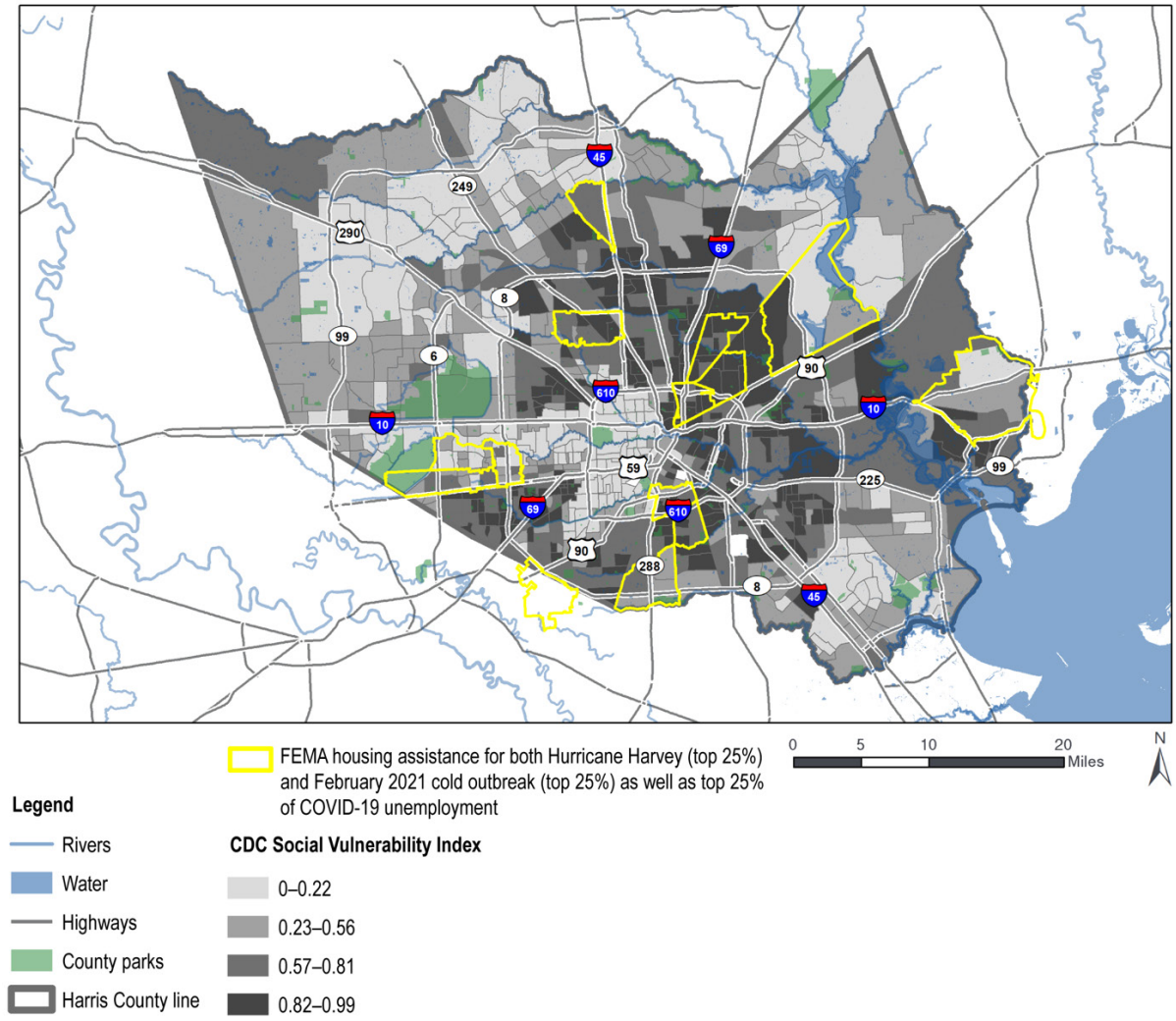
Houston is a city of 2.3 million people within a broader metropolitan area of 7.2 million.[39,40] It became a major port city because the navigable depth and orientation of the Buffalo Bayou supported the export of products from fertile inland croplands.[41] By the early 1900s, oil and gas production emerged, and companies moved into Houston to shelter from coastal storms after the catastrophic 1900 Galveston hurricane.[42] Now, Houston is one of the Nation's fastest-growing cities, and its port is the Nation's largest by tonnage. It is home to NASA's Johnson Space Center and the world's largest medical complex, the Texas Medical Center.

Demographically diverse, Houston residents are predominantly Hispanic (38%), White (35%), Black (17%), and Asian (8%).[43] One-quarter of Houstonians are foreign born, speaking almost 150 different languages. Social inequities and historic racism exacerbate many Houstonians' ability to prepare for, respond to, and recover from climate impacts. For example, 45% of Black and Hispanic residents do not have cash available to cover an unexpected $400 expense during an emergency, as compared to 13% for Whites and 7% for Asians.[44]

Houston experienced 35 federally declared disasters during 1982–2022; one-third of these were since 2015. Devastating floods occurred in April 2016 (the "Tax Day Flood"), August 2017 (Hurricane Harvey), September 2019 (Tropical Storm

Imelda), and September 2020 (Tropical Storm Beta). In August 2011, residents experienced 24 days of air temperatures above 98°F.[45] The February 2021 cold outbreak (Box 26.2) crippled much of Houston's energy and water systems. The effects of these disasters compound (Figure 26.3; Focus on Compound Events), amplifying harm to populations especially at risk.

## Compounding Damages in Houston, Texas, from a Hurricane, Cold Outbreak, and Pandemic




**Damages from compounding events—a hurricane, cold outbreak, and pandemic—disproportionately impacted socially vulnerable populations in Houston, Texas.**

**Figure 26.3.** Several areas in Houston (yellow outlines) that were most affected by Hurricane Harvey, the February 2021 cold outbreak (unofficially named "Uri"), and COVID-19 unemployment coincided with census blocks with high scores on the Social Vulnerability Index (SVI) from the CDC (darker gray shading). (The SVI measures 16 social factors that describe socioeconomic status, household characteristics, racial and ethnic status, housing type, and transportation access.) For the weather events, zip codes were ranked by number of valid registrants to FEMA's Individual and Households Program for financial assistance; for COVID-19, zip codes were ranked by percentage of population claiming unemployment insurance due to COVID-19, according to Texas Workforce Commission data from May 2020 to June 2021. The zip codes in the top 25% by those metrics are outlined in yellow. Adapted from Map 5 of Rice University's Kinder Institute for Urban Research 2022.[46]

Houston acted in response to these experiences and the scientific consensus on climate change. The city established a chief resilience officer in 2019. It published its Resilient Houston strategy and climate action plan in 2020[47] to prepare for, withstand, and recover from sudden catastrophic events and slow-moving disasters, including those worsened by climate change. In August 2020, Houston hosted the Nation's largest single-day, community-led effort to measure and map where urban heat was most severe. One month later, the city released its climate impact assessment,[48] illustrating how climate change is expected to affect Houston's future. Other initiatives included an urban prairie resilience project and a green stormwater tax-abatement program.

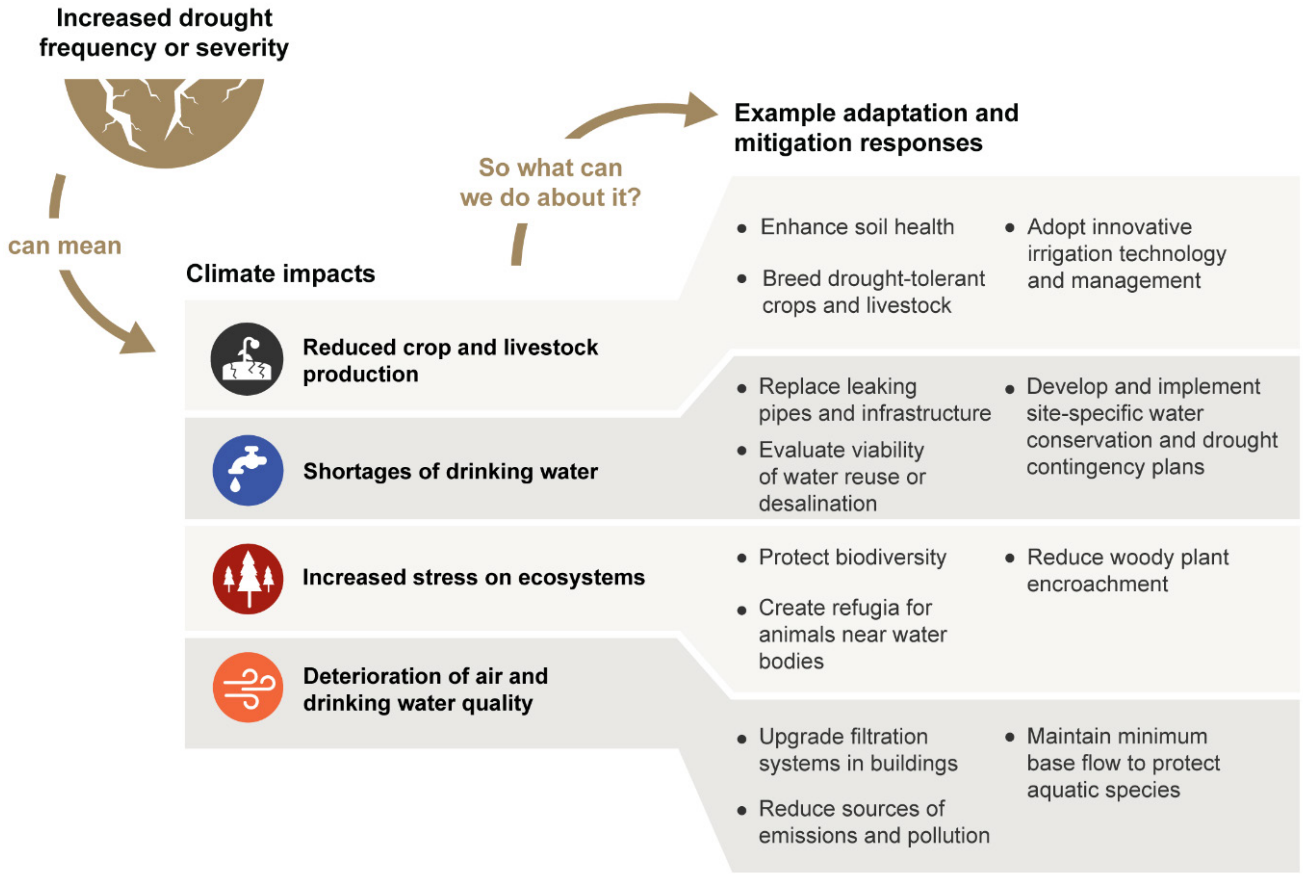
Climate change is also affecting public health through cardiovascular stress from temperature extremes, respiratory diseases enhanced by allergens and pollutants, increases in transmission of vector-borne diseases (e.g., via mosquitoes), and illnesses caused by poor water quality (KM 15.1). Many of these risks are compounded by ecosystem and land-use change. For example, global warming has induced earlier and longer pollen seasons, with consistent changes during the past three decades in Texas.[49] From 1987 to 2020, expansion of eastern red cedars was associated with a 205% increase in allergenic pollen intensity in Tulsa, Oklahoma.[50] During grass-pollen season, the region's emergency medical facilities are expected to see an average of 720 (under an intermediate scenario [RCP4.5]) to 980 (very high scenario [RCP8.5]) more asthma patients annually by 2050.[51]

High temperatures, particularly when combined with high humidity, have impaired human health. In Oklahoma, most heat-related deaths have occurred from July to September during heatwaves.[52] People who are male, Black, 65 years or older, diabetic, unmarried, without air-conditioning, or living below the poverty line have been at higher risk of heat-related death (KM 15.2).[52,53] Warmer temperatures also have worsened air pollution by increasing near-surface ozone.[54] In 2023, 18 Texas counties in the Dallas–Fort Worth and Houston–Galveston metropolitan areas exceeded national ozone standards (i.e., 8-hour ozone concentrations of 0.100 – 0.113 parts per million), affecting more than 12 million people.[55]

Rising temperatures are extending the ranges and lengthening the active seasons of ticks, mosquitoes, and other disease vectors (KM 15.1).[56] For instance, host-seeking activities of ticks, which usually suspend in cold temperatures, were reported during January and February 2017 in eastern Kansas and Oklahoma.[57] Warmer temperatures in the future are expected to support the range expansion of tropical diseases, including dengue, West Nile virus, Chagas disease, and chikungunya.[58] Across western parts of the region, future warmer and drier conditions are projected to support an increased incidence of Valley fever,[59] which is endemic in parts of Texas.[60]

Climate-smart planning (Figure 26.4) is alleviating some harmful consequences of climate variability and change that threaten residents' health. Urban tree canopy assessment,[61] planning,[62] and planting[63] efforts are aiming to reduce the negative impacts of increased temperatures, air pollution, and variable precipitation on urban landscapes.[64] Community food forests, such as the Osage Orchard in Pawhuska, Oklahoma, provide food sovereignty and security, climate resilience, and public health benefits.[65] Still, a lack of resources among many Tribes,[66] outdoor and migrant workers,[67] and overburdened populations[68] has limited the ability of these groups to respond to climate-related health risks.

### Resilience Actions to Address the Impacts of More Frequent or Severe Droughts on Communities




**Resilience actions can help alleviate harmful consequences to communities of more frequent or severe drought.**

**Figure 26.4.** The increasing frequency or severity of drought has negative impacts on lands and waters across the Southern Great Plains, including reduced crop and livestock production, shortages of drinking water, increased stress on ecosystems, and deterioration of air and drinking water quality. The example adaptation and mitigation actions can increase resilience and reduce negative impacts. Figure credit: See figure metadata for contributors.

## Key Message 26.2

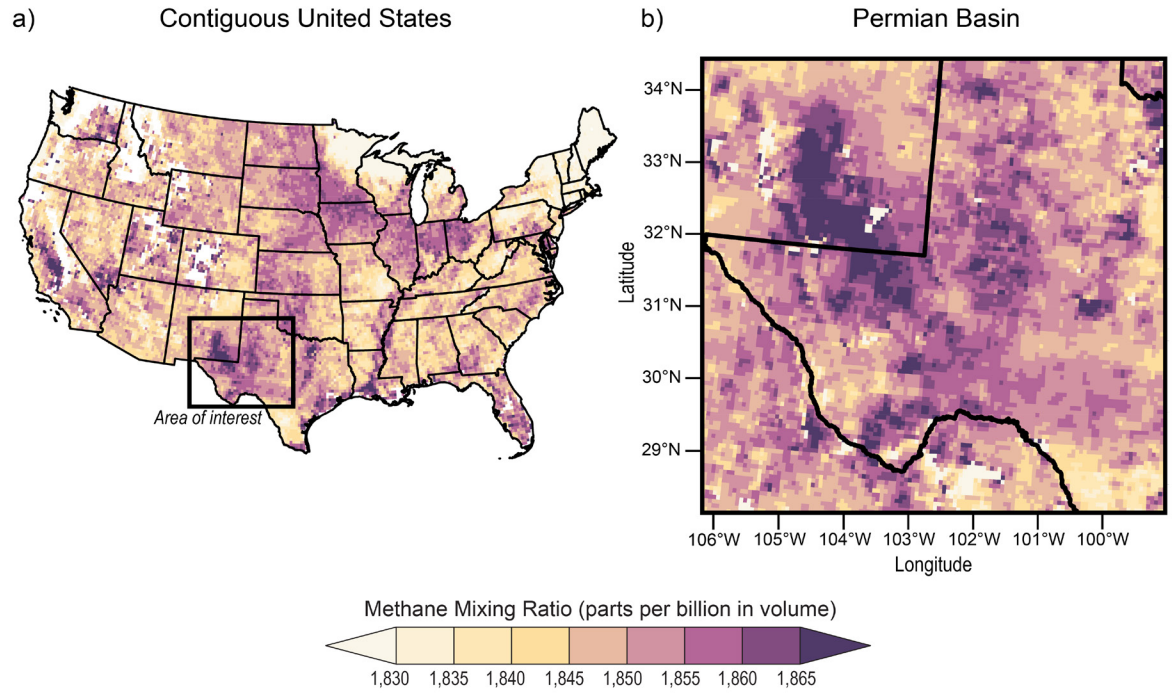
## How We Work: Climate Changes Are Creating Economic Challenges and Opportunities

As climate conditions change, businesses and industries across the Southern Great Plains are experiencing disruptions and losses in productivity and profits—but also new economic opportunities (*high confidence*). In coming decades, warmer temperatures, more erratic precipitation, and sea level rise are expected to force widespread and costly changes in how we work (*very likely*, *high confidence*). Businesses and industries have opportunities to harness their diverse knowledge, resources, and workers to develop products and services in climate mitigation technologies, adaptation strategies, and resilient design that will enhance the region's economy (*medium confidence*).

The region's economy provides for daily needs of residents, supports their long-term aspirations, and addresses societal needs inside and beyond the region. Hotter temperatures, heavier precipitation, stronger tropical cyclones, and other climate changes (App. 4) have harmed workers' health and productivity, inflated product or building costs, and disrupted supply chains (Focus on Risks to Supply Chains). Extreme weather events, such as the February 2021 winter storm (Box 26.2), have exposed gaps in the resilience of businesses to climate extremes while also highlighting opportunities to develop products and services in response to worldwide demand for resilient solutions.

The energy industry in the Southern Great Plains is a global leader in fossil fuel exploration and production, serving a large fraction of global energy demand and supporting rural towns through local employment and tax revenues.[69] Fossil fuels release greenhouse gases when burned, contributing substantially to atmospheric warming (KM 2.1). In 2020 Texas led the Nation in emissions of carbon dioxide ($CO_2$; 667 million metric tons)—double that of the next-highest emitting state.[19] Texas also had the highest methane emissions (94 million metric tons of $CO_2$ equivalent in 2020).[19] Natural gas operations in the Permian Basin leak the largest amount of methane per year from any US gas-producing region, an amount sufficient to supply natural gas to 7 million Texas households annually.[70] Atmospheric methane concentrations are high across the Permian Basin as compared to the rest of the US (Figure 26.5) and are attributed primarily to natural gas production.[70]

## Methane Across the Permian Basin (May 2018–March 2019)



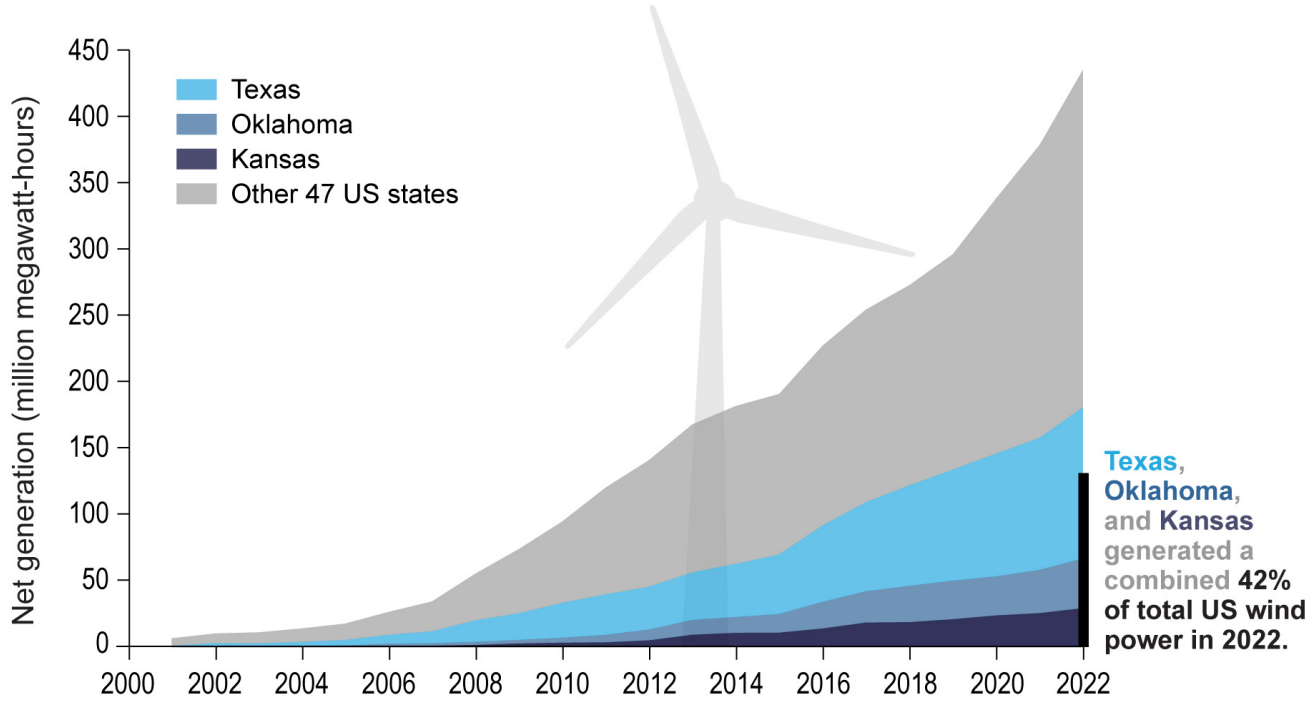

**Natural gas operations in the Permian Basin leak large amounts of methane.**

**Figure 26.5.** The maps show satellite-estimated methane mixing ratio (in parts per billion by volume [ppbv]) across (**a**) the contiguous United States and (**b**) the Permian Basin (black box and inset map), averaged from May 2018 to March 2019. Mixing ratio is a measure of the concentration of a gas such as methane in the air. Darker shading represents higher methane mixing ratios; missing data are shaded white. Accounting for atmospheric transport, the spatial pattern of methane mixing ratio across the basin is closely associated with gross (before processing) natural gas production and, to a lesser extent, with oil production. (The original published source did not include data for Alaska, Hawai'i and the US-Affiliated Pacific Islands, and the US Caribbean.) Natural gas operations in the Permian Basin leak a large volume of methane, contributing to atmospheric warming. Adapted from Zhang et al. 2020[70] [CC BY-NC 4.0].

Throughout the region, a major shift in energy generation from fossil fuels toward renewables (KM 5.3) is underway, creating new jobs, cleaner air, and climate change mitigation benefits. For example, the Electric Reliability Council of Texas (ERCOT; Texas's main power supplier) estimates that installed capacity for electricity generated by wind from their suppliers alone will increase from 31,100 MW in 2020 to 41,700 MW in 2025.[71] During the same time, ERCOT expects growth in solar generation capacity from 6,000 MW to 46,400 MW, and in battery storage from 275 MW to 14,500 MW. Electricity generated from gas and coal, however, is not planned to increase substantially.[71,72] In the third quarter of 2022, about 285,000 workers were employed in fossil fuel extraction, distribution, and support activities across the three states.[73] A transition of this workforce from a carbon-intensive to a low-carbon economy is expected to affect some Southern Great Plains communities disproportionately.[74] Within Tribes, a just transition also means a strengthening of Tribal sovereignty, economic independence, and nonextractive, Indigenous-based restoration of ecosystems.[3] For Tribes and communities facing this transition, there generally is a lack of planning, infrastructure, financing, and workforce training in new careers (including in renewable energy) across the region (e.g., Williams et al. 2021[75]).

The Southern Great Plains accounts for 42% of the Nation's wind-generated electricity (Figure 26.6).[18] Major wind installations in rural communities support the local tax base, stabilizing funding for public services such as education, road maintenance, and emergency services, as well as for infrastructure such as hospitals, jails, and parks.[76] Wind-turbine productivity across western Kansas, western Oklahoma, and the Texas Panhandle is projected to increase with climate change because of a more stable low-level jet stream—a regional atmospheric feature that generates strong winds at turbine height, particularly at night during spring and summer.[77]

## Net Generation of Electricity from Wind (2001–2022)




**The Southern Great Plains contributes a large share to total US wind-generated electricity.**

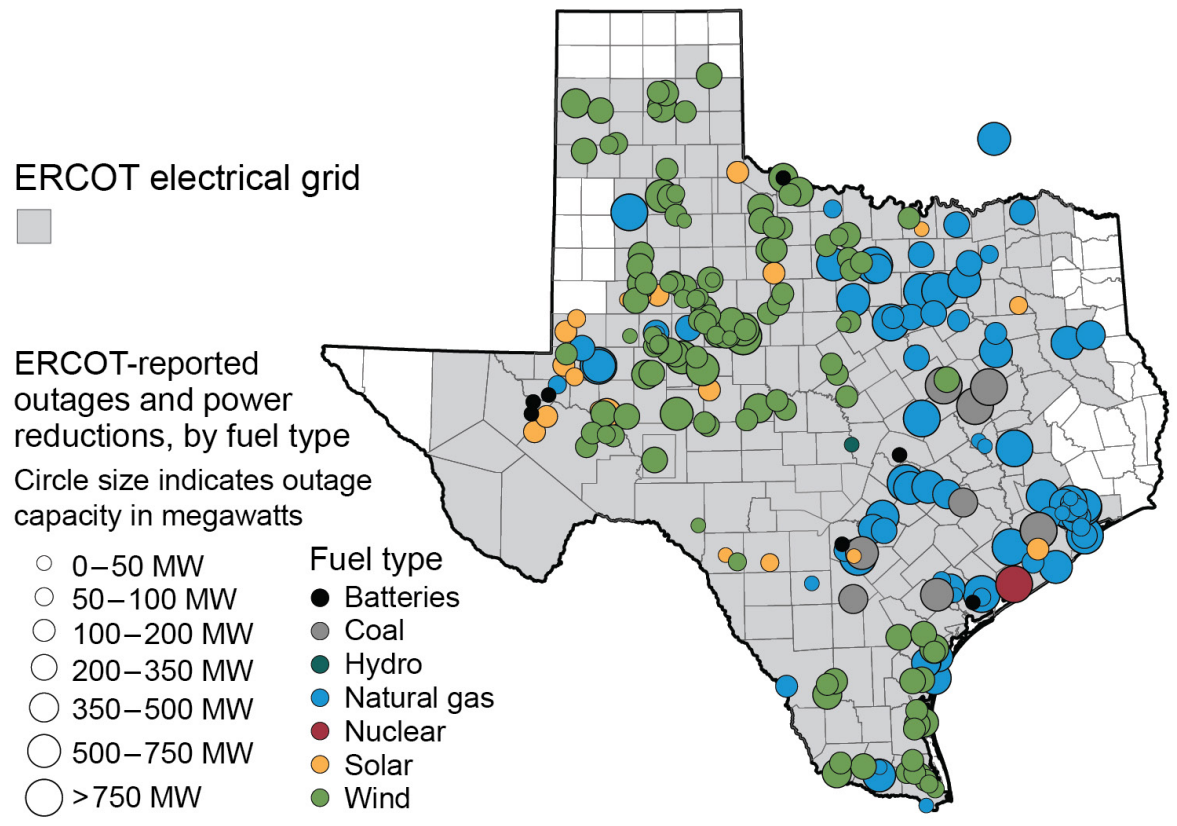
**Figure 26.6.** US producers in the 50 states generated 435 million megawatt-hours of electricity from wind power in 2022. Together, Texas, Oklahoma, and Kansas contributed 159 million megawatt-hours, or 42% of total US production. Data were not available for the US-Affiliated Pacific Islands or the US Caribbean. Figure credit: See figure metadata for contributors.

## Box 26.2. February 2021 Severe Cold Outbreak

Cold outbreaks occur when the jet stream weakens, causing Arctic air to advance southward. From February 8–20, 2021, Arctic air moved far into the Southern Great Plains.[78,79] Wind chills were below 0°F from central Texas northward on Valentine's Day, snow fell along the Texas Gulf Coast, and almost 3,000 daily minimum-temperature records were tied or broken across the region.[80] The prolonged cold caused large-scale power disruption, left 14.4 million households without tap water, and led to more than 200 deaths.[81,82]

Electricity-generation units failed in large numbers during the frigid conditions (Figure 26.7), requiring grid operators to implement rolling blackouts to try to avoid widespread, uncontrolled outages.[81,83] Most of the unplanned outages and reductions in available capacity were associated with problems with natural-gas (58%) and wind (27%) generation units.[83] The Electric Reliability Council of Texas (ERCOT) was particularly devastated, losing up to 34,000 megawatts of capacity—almost half of its all-time peak load for the winter—from February 15–17.[83] As a result, more than 4.5 million people lost power, some for up to four days. Millions had to boil water for drinking and cooking, and many cities issued water conservation orders because of low water pressure.[81] In Houston, data indicate that non-White populations disproportionately experienced outages, regardless of their income level (Figure 26.8). Economic losses in Texas were estimated at $85.6–$139.1 billion (in 2022 dollars).[84]

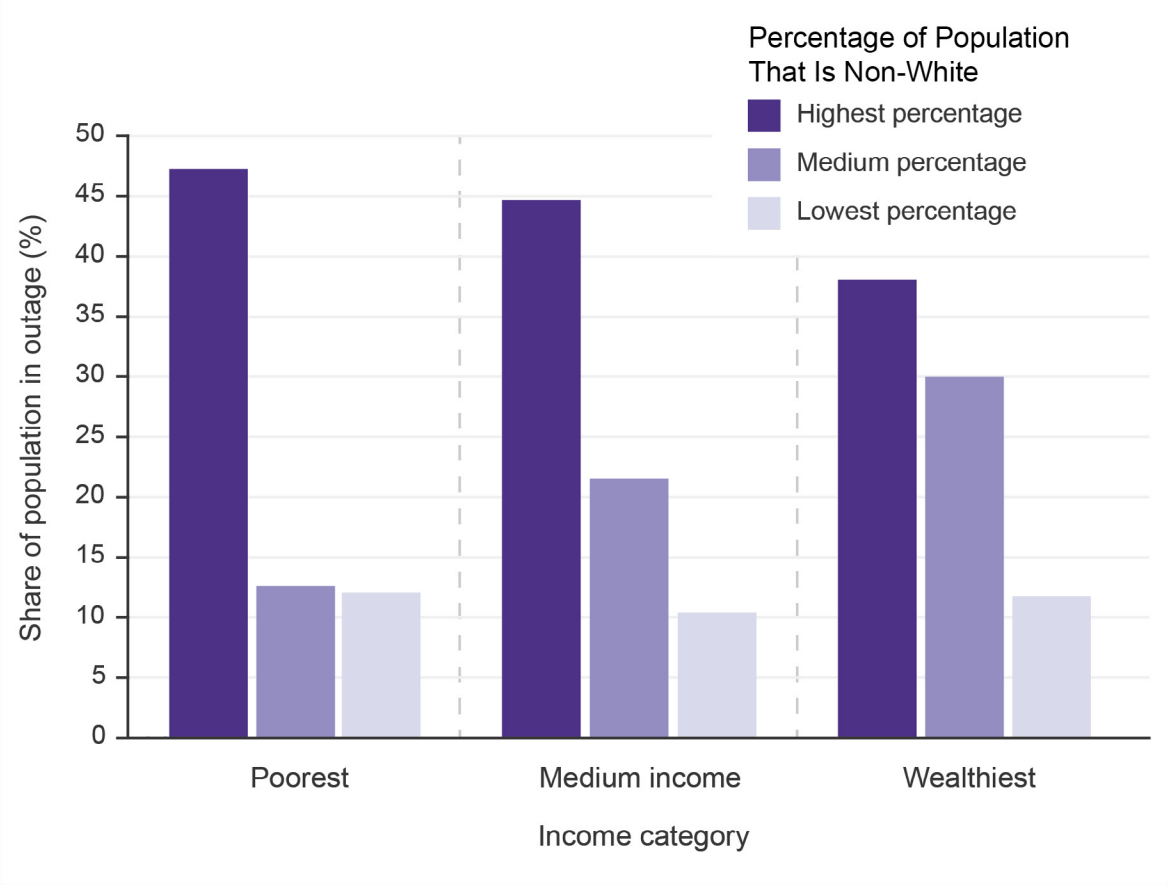
### Power Generation Outages During the Cold Outbreak in February 2021




**A severe cold outbreak in February 2021 led to extensive outages for electricity generation plants serving the Electric Reliability Council of Texas (ERCOT).**

**Figure 26.7.** The map shows the maximum outage or power reduction (in megawatts, MW) by location and fuel type for electricity generation facilities serving ERCOT during February 10–24, 2021, amid the cold outbreak across portions of the south-central US. Circles are colored by fuel type; larger circles represent larger values of maximum outage or power reduction. One generation facility is in Oklahoma. Shaded counties denote the ERCOT service area. In Texas alone, loss of generation capacity caused more than 4.5 million customers to be without power at some time during the cold outbreak.[83] Figure credit: See figure metadata for contributors.

## Income and Racial/Ethnic Disparities Related to Power Outages in Texas, February 2021




**Regardless of income level, non-White populations experienced a disproportionate share of outages during the February 2021 cold outbreak.**

**Figure 26.8.** This graph shows the percentage of the Texas population that experienced power outages during the February 2021 cold outbreak based on income level (poorest, medium income, and wealthiest) and race/ethnicity (lowest, medium, and highest percentage of non-White people in the population) by census block group. Non-White people are those individuals whose race was listed as other than White alone or who list their ethnicity as Hispanic or Latino. Regardless of wealth status, data indicate that areas with the highest populations of non-White people were the most likely to be impacted by power outages due to long-standing marginalization. Adapted with permission from Carvallo et al. 2021.[85]

The severe cold outbreak was not historically unprecedented, and widescale outages were avoidable.[78] To illustrate how good adaptation enhances resilience, the City of El Paso, Texas, had prepared for extreme cold following widespread energy and water disruptions in 2011. The city invested in winterization of power infrastructure and built a new power plant that could operate with different fuel types.[86] These adaptations, along with the city's connection to a different power grid, resulted in few outages during the 2021 event.

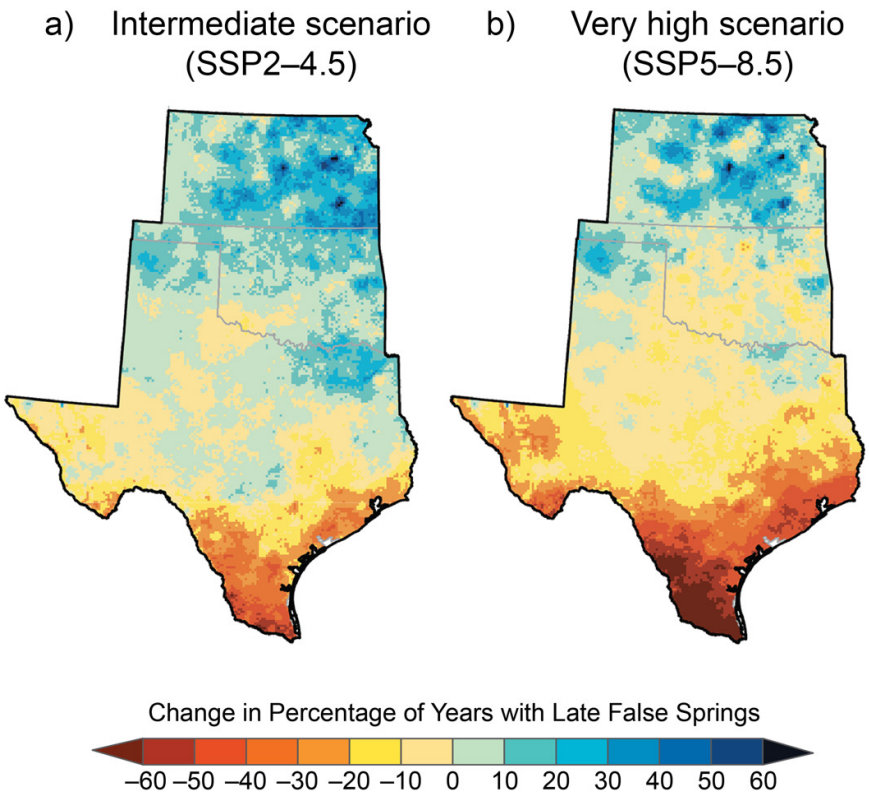
Although the effect of climate change on the jet stream's strength is an ongoing area of research[87] and extremely cold days are expected to decrease, projections indicate that the region will still experience extreme cold events in a warming world.[88] These events are expected to result in considerable costs if businesses are not adequately prepared.[78] In June 2021, the Texas legislature passed Senate Bill 3, which focused on improving emergency communication and gas infrastructure as well as other winter preparedness actions.[89] Grid operators also developed recommendations to improve energy reliability, grid operations, and communications for future winter weather events.[83]

Agriculture, including crop and livestock production and forestry, is an essential industry in the region. In 2022, Kansas led the Nation in grain sorghum production and ranked second nationally in all wheat production.[90] In 2023, Texas was first in head of cattle and calves, with Kansas and Oklahoma ranking third and fifth, respectively.[91] In 2017, the region's agricultural industry generated $60.5 billion (in 2022 dollars) in agricultural product sales, 70% of which was animal based.[92]

Agricultural producers are experiencing loss of livestock and crops, reduced income, and negative public health outcomes as climate extremes increase in magnitude and frequency (KMs 11.1, 11.2). Warmer average temperatures are leading to longer growing seasons, which affect different species differently and potentially disrupt the long-term natural connection between plants and their pollinators or between insects and their predators (KM 8.2).[93] Historical plant hardiness zones are predicted to continue migrating northward as the annual average minimum winter temperature warms (Figure 11.3). High temperatures have reduced plant growth and diminished productivity.[94] In western Kansas and the Oklahoma and Texas Panhandles, the combination of cold fronts and earlier springs is projected to increase the potential for bud burst before the last freeze (Figure 26.9),[95] threatening plant-leaf and wood-tissue damage.[96]

Compound events (Focus on Compound Events) that encompass hot, dry, and windy conditions have increased in southwest Kansas and the Panhandles of Oklahoma and Texas, reducing wheat yields proportionally to the number of hot-dry-windy hours.[97,98] Producers also are expected to experience drier conditions (Figure 26.10) and more frequent or intense drought by midcentury in western and southern parts of the region, lowering crop productivity or increasing irrigation costs.[99] By 2070 across a range of climate change scenarios (from low [RCP2.6] to very high [RCP8.5]), the Southern Great Plains is projected to lose cropland acreage, as these lands transition to pasture or grassland.[100]

## Projected Change in Annual Risk of Late False-Spring Events



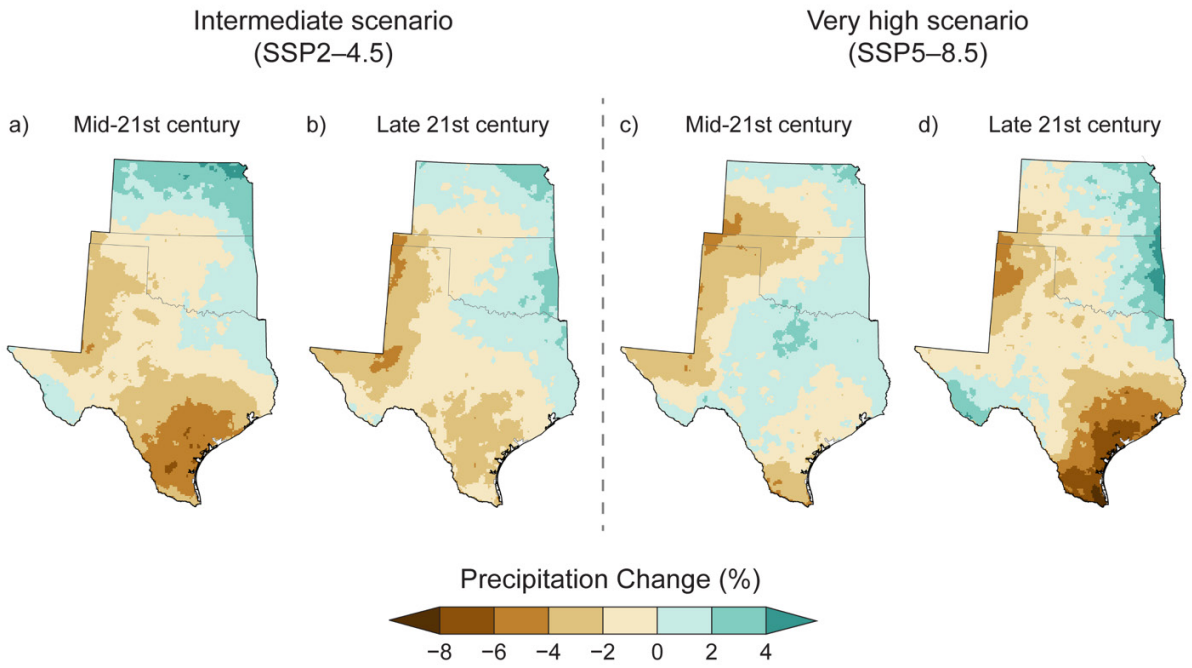

**The risk of plant bud burst before the last freeze is projected to increase for the northern portion of the Southern Great Plains. The risk decreases for the southern portion of the region.**

**Figure 26.9.** Freezing temperatures after plants begin growth in spring (late false spring) can damage crops and nursery plants. Risk of a late false spring is projected to increase in northern parts of the Southern Great Plains by the end of the century (2071–2100) as compared to the 1991–2020 average. The risk of late false springs increases by up to 20% across most of Kansas, Oklahoma, and northern Texas under an intermediate scenario (SSP2-4.5; panel **a**) and across most of Kansas, the Texas Panhandle, and parts of Oklahoma under a very high scenario (SSP5-8.5; panel **b**). Risk decreases for the remainder of the region, especially in southern and far western Texas under a very high scenario. Figure credit: See figure metadata for contributors.

Although increasing irrigation during drought can help maintain productivity, it reduces groundwater available for other ecological or societal needs and for future generations. Growers can produce similar yields using less water by adopting more efficient irrigation technologies and management practices.[101] Neighbors also can help neighbors. For example, irrigators in Sheridan and Thomas Counties (Kansas) self-imposed annual water restrictions that reduced water usage by 26%, with no reduction in crop acreage.[102]

Drought also has reduced the capacity of native rangelands and planted pastures to support livestock and has increased labor demands for feeding, forcing producers to sell genetically valuable animals. High temperatures also pose risks to animal health.[99] In June 2022, for example, thousands of cattle died in southwestern Kansas during a heatwave combined with high humidity and low wind speeds.[103,104] The additional stressors from climate change are anticipated to be especially difficult for multigenerational ranchers who strive to earn a profit while preserving the health of lands for their descendants.[105] For large-scale livestock production, successful adaptation to a changing climate includes enhancing soil health and reducing the number of animals per acre.[106]

## Projected Change in Total Annual Precipitation



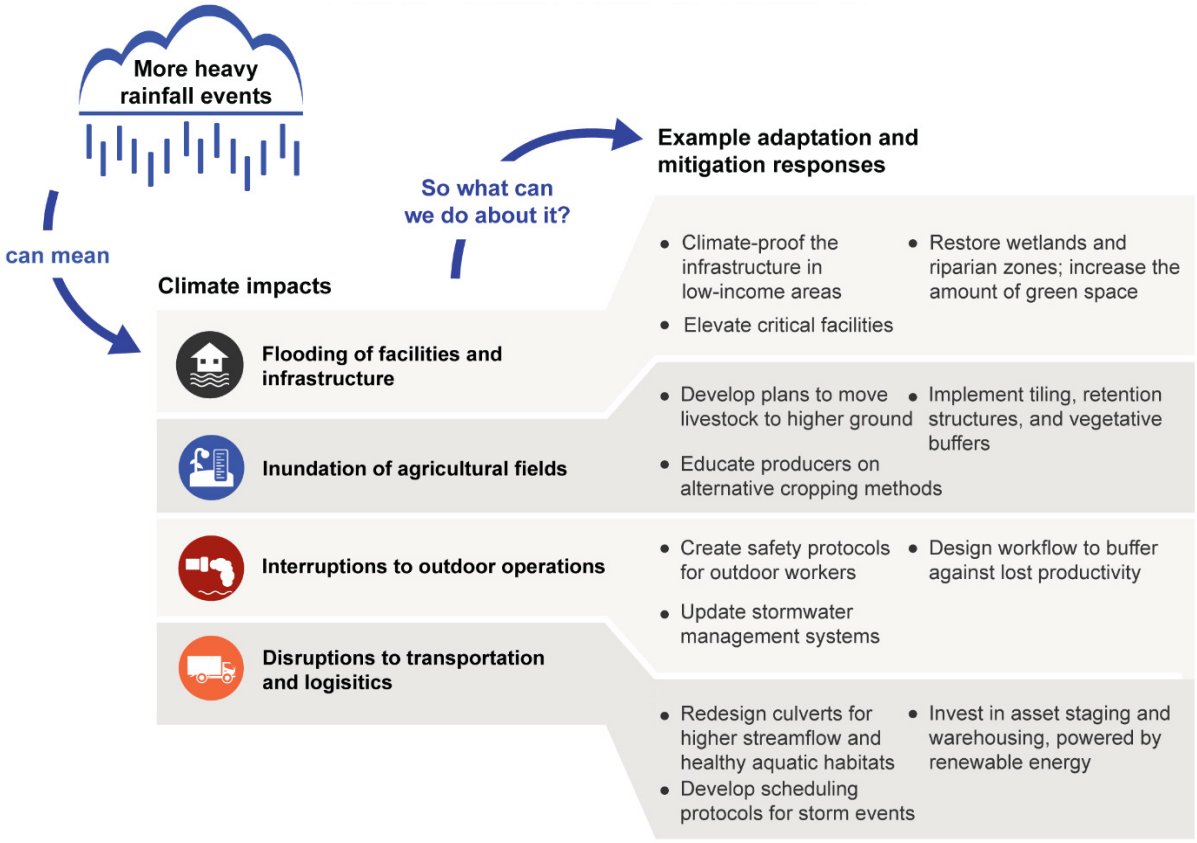

**Slightly drier conditions are projected for much of the western and southern portions of the region by the end of the century.**

**Figure 26.10.** In the future, drier conditions threaten agriculture and water supplies in parts of the Southern Great Plains (brown), while more precipitation is projected near the northern and eastern boundaries of the region (green). Under an intermediate scenario (SSP2-4.5), total annual precipitation is projected to decrease by 4% or more (as compared to the 1991–2020 average) in southern Texas by midcentury (**a**), with smaller differences expected by century's end (**b**). Under a very high scenario (SSP5-8.5), annual precipitation is projected to decline slightly in western portions of the region by midcentury (**c**) and by 4% or more in southeast and far northwest Texas by the century's end (**d**). Figure credit: See figure metadata for contributors.

More broadly, climate change–related damages to businesses have threatened the continuity of operations, increased insurance costs, disrupted supply chains, and shifted customer demand (KM 19.3). Many small businesses in the US do not have business disruption insurance, and 20%–40% of small businesses that temporarily close after a natural disaster do not reopen.[107] Small businesses owned by women, non-Whites, and veterans have a higher likelihood of closing after experiencing a natural disaster.[108] These closures have negatively affected the economy and well-being of local communities.[109]

Large and small businesses and industries have started efforts to mitigate greenhouse gas emissions. For example, in 2021 Amazon piloted an electric-vehicle fleet in Tulsa, Oklahoma, and in 2022 Frito-Lay did likewise in Carrollton, Texas. The need to reduce emissions on a worldwide scale presents economic opportunities for energy-related businesses in the region to pilot and develop new technologies. NRG Energy and JX Nippon, for example, partnered to create a commercial-scale carbon capture facility at NRG's coal-fired Petra Nova power plant in Thompsons, Texas.[110] It was the US's first and only facility to capture over one million tons of $CO_2$ per year. It suspended operations in 2020, however, because oil prices were too low to justify the expense of using the captured $CO_2$ for enhanced oil recovery.[111] Houston's Sage Geosystems is testing how to generate geothermal energy at commercial scale by repurposing an existing oil well in San Isidro, Texas,[112] and groups like Kansas Soil Health Alliance and Texas Coastal Exchange are supporting carbon storage through soil and land stewardship.[113,114] Mitigation and adaptation actions by businesses and industries promote resilience and offer long-term benefits to employers, employees, and the surrounding community (Figure 26.11).

### Resilience Actions to Address the Impacts of Heavier Rainfall Events on Businesses




**Resilience actions can help businesses and industries reduce the negative consequences of more heavy rainfall events.**

**Figure 26.11.** An increased number of heavy rainfall events affects business and industry across the Southern Great Plains through flooding of facilities and infrastructure, inundation of agricultural fields, interruptions to outdoor operations, and disruptions to transportation and logistics. The example adaptation and mitigation actions can increase resilience and reduce negative impacts. Figure credit: See figure metadata for contributors.

## Key Message 26.3

## How We Play: Climate Extremes Are Endangering Sports, Recreation, and Leisure

Extreme climate-related events are negatively influencing how we play and participate in outdoor sport, recreation, and physical activities in the Southern Great Plains (*very high confidence*). Climate change is expected to increase heat-related illness and death, reduce outdoor physical activity, and decrease athletic performance (*very likely*, *high confidence*). Individuals, communities, and sports organizations can adapt to these hazards through strategies such as modifying the timing, location, intensity, or monitoring of activities (*high confidence*).

Sports, recreation, and leisure activities are part of life in the Southern Great Plains. Hunting, fishing, jogging, playing on the playground, and other activities help maintain participants' physical and mental

health. Organized sports, such as football, soccer, and softball, bring together spectators to cheer for their favorite athlete or team, encouraging social cohesion.[115] Climate extremes have affected many of these activities, diminishing their benefits (Figure 26.12). For example, sports fields across southeastern Texas were closed because of flooding after Hurricane Harvey in 2017.[116] Although superintendents of unaffected schools offered Harvey-displaced students the opportunity to play on their teams, these athletes were reluctant to forfeit their home-team eligibility, reducing their broader scholastic involvement.[117]

Athletes of all ages experience decreased performance, do less outdoor physical activity, and are at higher risk of severe to fatal health issues because of extreme heat, air pollution, and weather hazards.[118,119] These risks especially apply to older adults, those with chronic disease or higher body mass index, and those under prolonged environmental exposure (e.g., marathon runners) who conduct high-intensity sports or wear clothing or equipment that prevents heat loss.[120,121] Heat injuries can damage organs (e.g., liver, muscle, kidney) or disrupt the central nervous system.[122]

All dimensions of environmental injustice (i.e., recognitional, distributional, and procedural; Figure 20.1) intersect with climate change to disproportionately harm people who have been marginalized (KM 15.2), reducing their participation in and health benefits from outdoor physical activities. These people include low-income populations, those living in areas with higher levels of air pollution, and those with less access to places to engage in sports, recreation, and leisure.[123,124] Non-English-speaking recreationists are at increased risk because health communication about climate-related hazards (such as the dangers of swimming in a harmful algal bloom) likely is not presented in their native language.[125]

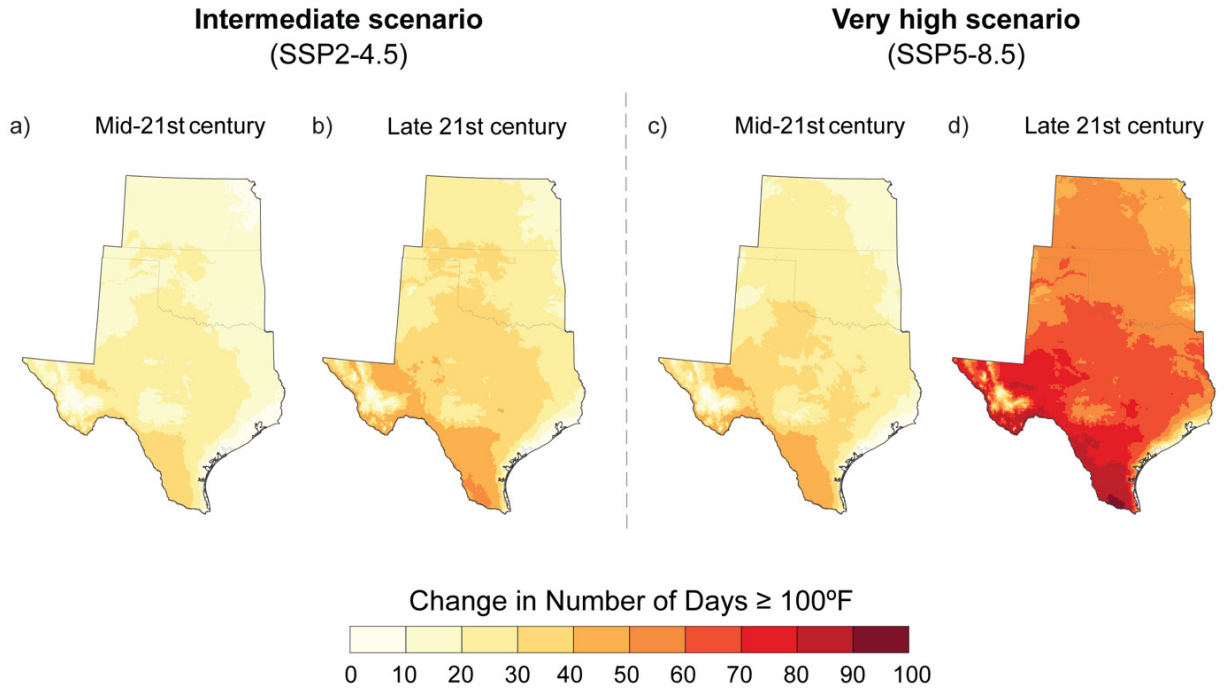
## Climate Change Impacts on Outdoor Activities

**Climate change is expected to affect many outdoor sports, recreational, and leisure activities.**

**Figure 26.12.** Outdoor sports, recreational, and leisure activities for people of all ages are being affected by climate extremes. Heavy rainfall, poor air quality, and extreme heat are expected to increase with climate change. These stressors impair athletic performance, damage sports facilities, and alter landscapes for recreation and tourism. Figure credit: See figure metadata for contributors.

Nationally, heat-related illnesses are the third-highest cause of death among high school athletes[126] and are the most preventable cause of death in youth sports.[127] Heat-related deaths can occur outside of a typical heatwave. For players of organized football at any level, these types of death occurred most often in the south-central and southeastern United States.[128] These risks apply to any outdoor sport, especially those that involve training or competition during summer and fall. Future increases in the number of very hot days and warm nights are expected to exacerbate health concerns (Figure 26.13). For example, the number of 100-degree days is projected to increase by the end of the century under a very high scenario (SSP5-8.5) by 30–60 days in Kansas and Oklahoma and more than 80 days in parts of southwestern Texas (Figure 26.13c, d). By contrast, under an intermediate scenario (SSP2-4.5), the number of 100-degree days per year would remain close to the recent average (Figure 26.13a, b).

## Projected Change in Annual Number of Days of 100°F or Higher




**The number of extreme-heat days is projected to increase.**

**Figure 26.13.** Outdoor physical activity becomes more dangerous in extremely hot temperatures. By midcentury, the number of days per year with temperatures at or above 100°F across the Southern Great Plains is projected to increase (**a**) by 10–40 days under an intermediate scenario (SSP2-4.5) and (**c**) by 10–60 days under a very high scenario (SSP5-8.5) above the 1991–2020 average. By late century, projections indicate that the number of these extreme-heat days would increase (**b**) by 10–60 days (SSP2-4.5) or (**d**) by 30–90 days (SSP5-8.5), depending on scenario. The historical average ranges from fewer than 10 days per year in Kansas to fewer than 20 days across most of Oklahoma and Texas, with 40–60 days along the Mexican border. Figure credit: See figure metadata for contributors.

Extreme temperatures have threatened the health of young athletes and their ability to practice and compete outdoors in sports like cross-country, track and field, tennis, golf, softball, soccer, and lacrosse.[129,130,131] In schoolyards or playgrounds, the time spent playing in warm or hot environments and the physical environment (e.g., shade, vegetation) have affected the perceived discomfort of youth while they are active outdoors.[132] Unhealthy heat stress is occurring even at ambient temperatures of 80°–85°F where play areas are unshaded and have artificial surfaces (e.g., asphalt or artificial turf).[133] Children from non-White and lower-income families have less access to high-quality, sizeable urban parks,[134] putting them at higher risk of heat illness and other adverse health outcomes (i.e., physical and mental health problems).[123]

Heavy rainfall and extreme temperatures cause sports teams to depend more on artificial or indoor environments, increasing participation costs and decreasing access to sports, especially for lower-income populations.[120] The Texas Rangers replaced their structurally sound stadium earlier than expected because extreme temperatures suppressed attendance.[135] The new stadium has a retractable roof for a climate-controlled environment. Sports events across all levels—from youth and interscholastic to collegiate and professional—have been halted or moved because of the unusual timing or intensity of storms (Figure 26.14, left), resulting in scheduling challenges, economic costs, and reduced social interactions.[136,137] All people who enjoy the outdoors as part of their healthy lifestyle are expected to face more days with dangerous extreme heat (Figure 26.14, right).

## Extreme Event Impacts on Sports and Recreation

**Outdoor sports and recreation of all kinds are challenged by extreme events.**

**Figure 26.14.** (**left**) University of Oklahoma staff paint the Green Wave of Tulane University on their football field for a September 4, 2021, matchup. The game was relocated after Hurricane Ida left Tulane's stadium powerless and damaged. (**right**) As people enjoy the outdoors as part of a healthy lifestyle, warmer temperatures are expected to cause them to adapt by drinking cool liquids, reducing strenuous exercise, or exercising during cooler times of the day. Photo credits: (left) ©University of Oklahoma Athletics; (right) ©Emma Kuster.

Lakes, streams, and reservoirs support fishing, hunting, and other outdoor recreation; however, more variable or heavier rainfall, flash or prolonged droughts, and higher temperatures have jeopardized recreation by reducing the quality and quantity of water.[138] In 2019, for example, southeast Kansas and northeast Oklahoma experienced historic spring flooding after multiple storm systems brought almost 2 feet of rain.[139] The flooding caused more than $12.5 million (in 2022 dollars) in damages for the Kansas Department of Wildlife, Parks, and Tourism (Figure 26.15), primarily through lost revenues from park closures.[140] Texas State Parks amassed a $5.9 million (in 2022 dollars) funding deficit when drought, wildfires, and record heat prompted fewer visitors in 2011–2012.[141]

## Flooding of Park in Kansas, Spring 2019

**Historic spring flooding in 2019 closed parks and recreational areas in southeastern Kansas.**

**Figure 26.15.** Sandstone Bluff Cabin along Toronto Lake in Cross Timbers State Park was flooded from spring 2019 storms, as the lake level exceeded prior historic records. The extreme rainfall closed parks and created an estimated $12.5 million (in 2022 dollars) in damages. Photo credit: ©Kansas Department of Wildlife and Parks.

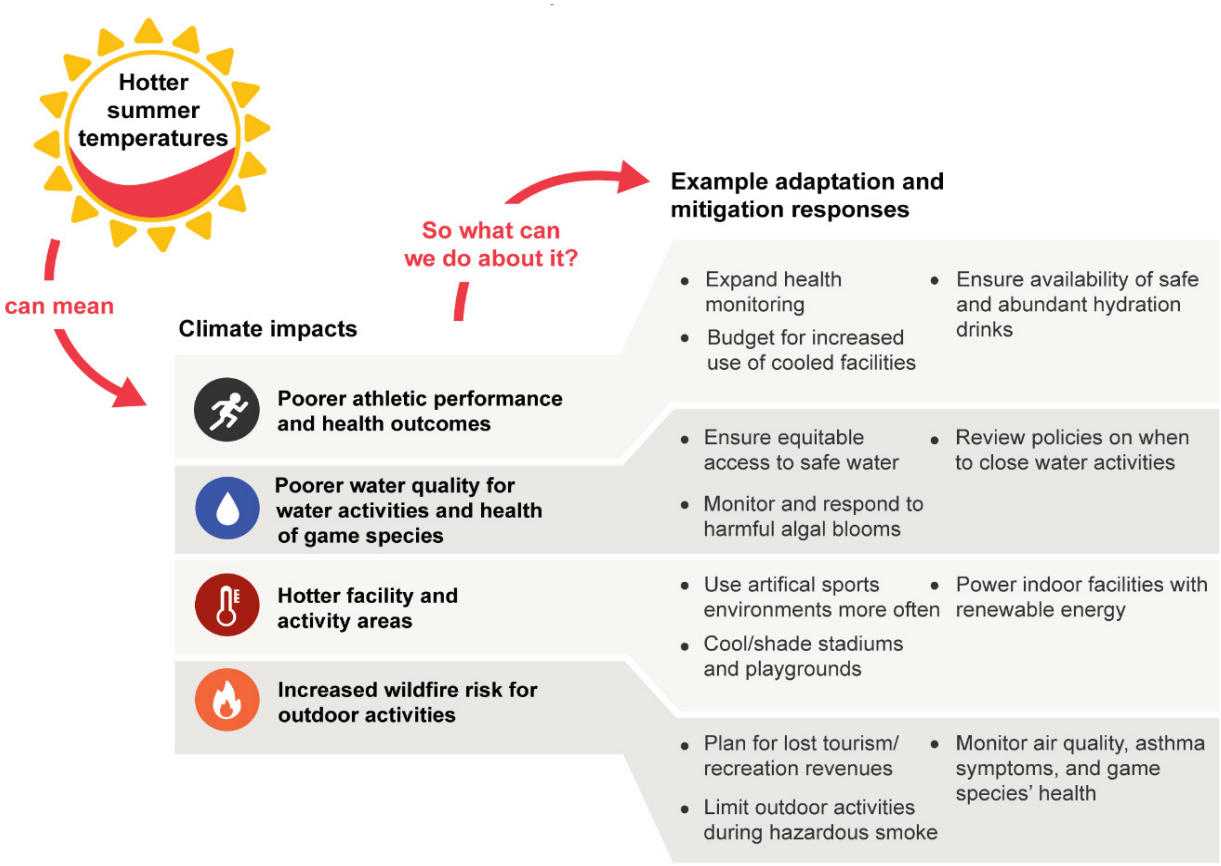
Along the Texas Coast, recreational opportunities are expected to change as coastal ecosystems transform, degrade, or disappear as a result of sea level rise (KM 9.1), warming temperatures,[142] and more powerful or rainier tropical cyclones.[143] After the destruction from Hurricane Harvey (2017), coastal ecotourism collapsed across the Coastal Bend, where ecotourism supports 8% of the local workforce and generates over a billion dollars in economic value annually.[144] Sea level rise has caused erosion of coastal beaches. Sand erosion on Galveston Island, for instance, has increased by 45% in comparison to geologic rates.[145] Sea level rise is also increasing saltwater inundation of coastal marshes that support birdwatching and angling.[146]

Changes in the timing and amount of precipitation have affected freshwater runoff and its associated salinity of bays and coastal ecosystems.[147] In the winter of 2008–2009 at the Aransas National Wildlife Refuge, a combination of inundation, drought, and upstream water use resulted in the loss of 10% of blue crabs, the main food source for the whooping cranes that draw legions of birdwatchers to the refuge.[148] Other impacts are favorable for coastal fisheries. Fewer extreme freeze events have caused the northward expansion of mangroves,[142] increasing fish diversity in Texas bays.[149] The diversity and prevalence of marine fish for sport fishing has also increased along Texas coasts as tropical fish expand their range northward.[150]

In 2020, hunting, shooting, and trapping generated $1.3 billion (in 2022 dollars) in Texas, ranking it first in the Nation.[151] Competition for limited food and water resources during drought is anticipated to alter animal migration, reproduction, and behavior (e.g., Cady et al. 2019;[152] Porro et al. 2020[153]). As a result, with warming temperatures, hunters are expected to see shifts in wildlife habitats and species ranges and decreases in the size and weight of prey.[154,155] For example, the Texas Parks and Wildlife Department has noted a decline in wintering mallard duck populations because open waters and food remain available farther north as winters warm.[156]

Sport, recreation, fish, and wildlife managers can plan for climate change by considering ways to alleviate negative impacts or enhance benefits (Figure 26.16). For example, to reduce health risks resulting from extreme heat, athletes can acclimatize to heat by slowly increasing the duration and intensity of exercise, scheduling strenuous outdoor activities during cooler hours, and reducing their core body temperature by applying ice packs and drinking cold water.[122] To maximize public outreach, communication of these risk-reduction methods should reflect the languages spoken throughout the community. Communities can support local sports, leisure, and recreation through landscape design by adding shaded green spaces as shelter from extreme heat. Park amenities, such as trees and splash pads, can also cool people on hot days. Despite the potential for temporary closures, siting parks and recreational areas along streambeds can reduce flood losses by buffering floodwaters in downstream developed areas.[157]

## Resilience Actions to Address the Impacts of Hotter Summer Temperatures on Outdoor Activities




**Resilience actions can alleviate the effects of hotter temperatures on outdoor activities.**

**Figure 26.16.** Hotter temperatures affect athletic, recreational, and leisure activities outdoors across the Southern Great Plains, leading to poorer athletic performance and health outcomes, poorer water quality, hotter facilities and activity areas, and increased wildfire risk. The example adaptation and mitigation actions can increase resilience and reduce negative impacts. Figure credit: See figure metadata for contributors.

## Key Message 26.4

## How We Heal: Climate Change Is Exacerbating Existing Social and Environmental Disparities

Some neighborhoods and communities in the Southern Great Plains are suffering disproportionately from climate-related hazards because of long-standing marginalization, discrimination, and governmental policies (*very high confidence*). As a result, climate change will compound existing social and environmental burdens on the people, neighborhoods, and communities with the fewest resources to prepare and adapt (*very high confidence*). Our institutions and governments can play a role in improving outcomes for these people and places by adopting climate adaptation and hazard-mitigation practices and policies that prioritize social equity and justice, aim to reduce community risks, build resilience, and repair past injustices (*medium confidence*).

Climate change does not affect all people in the same ways; society's most under-resourced and overburdened face harsher experiences (KMs 15.2, 20.1)[158] and have less access to climate-resilient infrastructure and recovery support,[159,160] typically as a result of power imbalances or discriminatory policies and practices.[161,162] This unequal distribution of harms and benefits is climate injustice. Those most impacted by climate inequities and injustices include people with low incomes; rural residents; disabled persons; older adults; Black, Indigenous, and People of Color; those who identify as other than cis, straight men; immigrants; those living in *colonias* (Texas-border housing developments lacking basic infrastructure and services); and unhoused individuals (KM 15.2).

Governments and organizations trying to heal historical traumas, injustices, and disparities are expected to face increasing urgency for equitable solutions and resources, as exposure to climate change impacts is projected to increase by midcentury. Lack of resources, political power, and technical expertise inhibit effective planning for and implementation of climate mitigation and adaptation.[3,163] Without intervention, climate change is expected to continue limiting equitable access to resources, services, and economic opportunities.

In many cases, housing stocks that serve low-income communities and communities of color lack adequate weatherization, air-conditioning, structural resistance to high winds, or adequate tree canopy, shade, and green spaces to provide heat relief due to long-standing under-resourcing and marginalization.[164,165] Lack of access to reliable and affordable energy increases the vulnerability of low-income communities to intense heat events. Severely marginalized groups, such as unhoused, detained, or incarcerated people, have experienced considerable suffering during extreme heat events with little relief.[166,167] For example, Texas inmates and correctional officers have endured heat stress or heat mortality from lack of air-conditioning and proper ventilation.[168]

Low-income communities and communities of color often lack access to adequate and maintained flood infrastructure, which reduces resilience, limits recovery, and contributes to increased flood vulnerability.[169,170] In Houston and other Gulf Coast communities, for example, these populations often live in lower-quality housing in flood-prone areas, placing them at a higher risk than those living in surrounding areas.[171]

In addition, low-income residential areas and residents of color tend to be in closer proximity to petrochemical plants or chemical storage facilities than their higher-income or White counterparts,[172] putting them at higher risk of industrial accidents caused by extreme weather events that release toxins into the air

and water (KM 15.2).[173] For instance, facilities that reported chemical releases after Hurricane Harvey tended to be near predominantly Hispanic neighborhoods and revealed patterns of societal inequity.[174] Exposure is particularly acute near Superfund sites[175] and across industrial areas of the Texas Gulf Coast (Figure 26.17).[176]

After a disaster, many people who are poor, uninsured, and without access to climate recovery and adaptation programs, such as voluntary buyouts, have not rebuilt.[159,177] Efforts to recover from compounding hazards (Focus on Compound Events) can quickly exhaust resources and strain mental well-being in low-income populations (KM 15.1).[178]

## Increased Climate Risks in Port Arthur, Texas

**Historically underserved communities near chemical facilities face increased risks from weather hazards associated with climate change.**

**Figure 26.17.** These scenes from Port Arthur, Texas, reveal (**top**) a low-lying landscape of petrochemical facilities and residential neighborhoods, representative of many communities along the Texas Gulf Coast. After Hurricane Harvey (2017) made landfall near Port Aransas, Texas, neighborhoods (**bottom left**) and transportation infrastructure and petrochemical facilities (**bottom right**) were flooded, exposing residents to contaminated waters spreading across the landscape. With climate change projected to intensify hurricanes and bring heavier rainfall, the risks to communities along the Gulf Coast are even higher when hazardous facilities, such as petrochemical plants, are nearby. Photo credits: (top) halbergman/iStock via Getty Images Plus; (bottom left) US Air National Guard Staff Sergeant Daniel J. Martinez; (bottom right) ©Alison A. Tarter.

Communities with insufficient capacity to evacuate prior to coastal storms are at greater risk from tropical cyclones, which are projected to be stronger by midcentury (KM 2.2). These communities also face increased likelihood of house abandonment as Gulf waters rise and rainfall becomes more intense.[160] After Hurricane Ike (2008), for example, over half of Galveston's public-housing apartments sustained damages, displacing

almost 600 households. Most of these apartments were demolished and not replaced, and displaced residents confronted barriers to participating in post-disaster decision-making.[179]

Settler colonialism and policies to eradicate Indigenous Peoples, cultures, and practices have contributed to current inequalities in climate mitigation and adaptation resources (KMs 15.2, 16.2, 20.2).[3] Through the Indian Removal Act and treaties with the United States,[180] Tribes became bound geographically to predetermined jurisdictions, often in areas now at higher risk of climate change impacts (KM 16.2) or more exposed to climate hazards than their historical lands.[181] Self-determination, sovereignty, and self-governance, however, empower Tribes in the region to lead their own climate adaptation planning, transforming themselves into thriving communities of their own design (Box 26.3). Indigenous Peoples have knowledges and experiences to share with all peoples about how to live sustainably and adapt to climate changes.[182]

## Box 26.3. Adaptation Planning Led by the Tribes of Kansas, Nebraska, and Iowa

The Iowa Tribe of Kansas and Nebraska, Kickapoo Tribe in Kansas, Meskwaki Nation, Omaha Tribe of Nebraska, Ponca Tribe of Nebraska, Prairie Band Potawatomi Nation, Sac and Fox Nation of Missouri, Santee Sioux Nation, and Winnebago Tribe of Nebraska recognized the need to be #Rezilient (the social-media notation for Tribal resilience) in the face of climate change. Using grant funding obtained by the Sac and Fox Nation of Missouri, the Tribes worked to blend their cultural values, Indigenous Knowledges, and adaptation experience with Western science to create Tribal climate adaptation plans. They convened a series of workshops (Figure 26.18) to guide Tribal environmental professionals to customize plans for their unique communities. Beginning in 2019, Tribal elders, council members, environmental professionals, and subject-matter experts initiated Tribal Technical Teams to identify knowledge sources and prioritize risks.

## Collaboration to Develop Tribal Climate Adaptation Plans

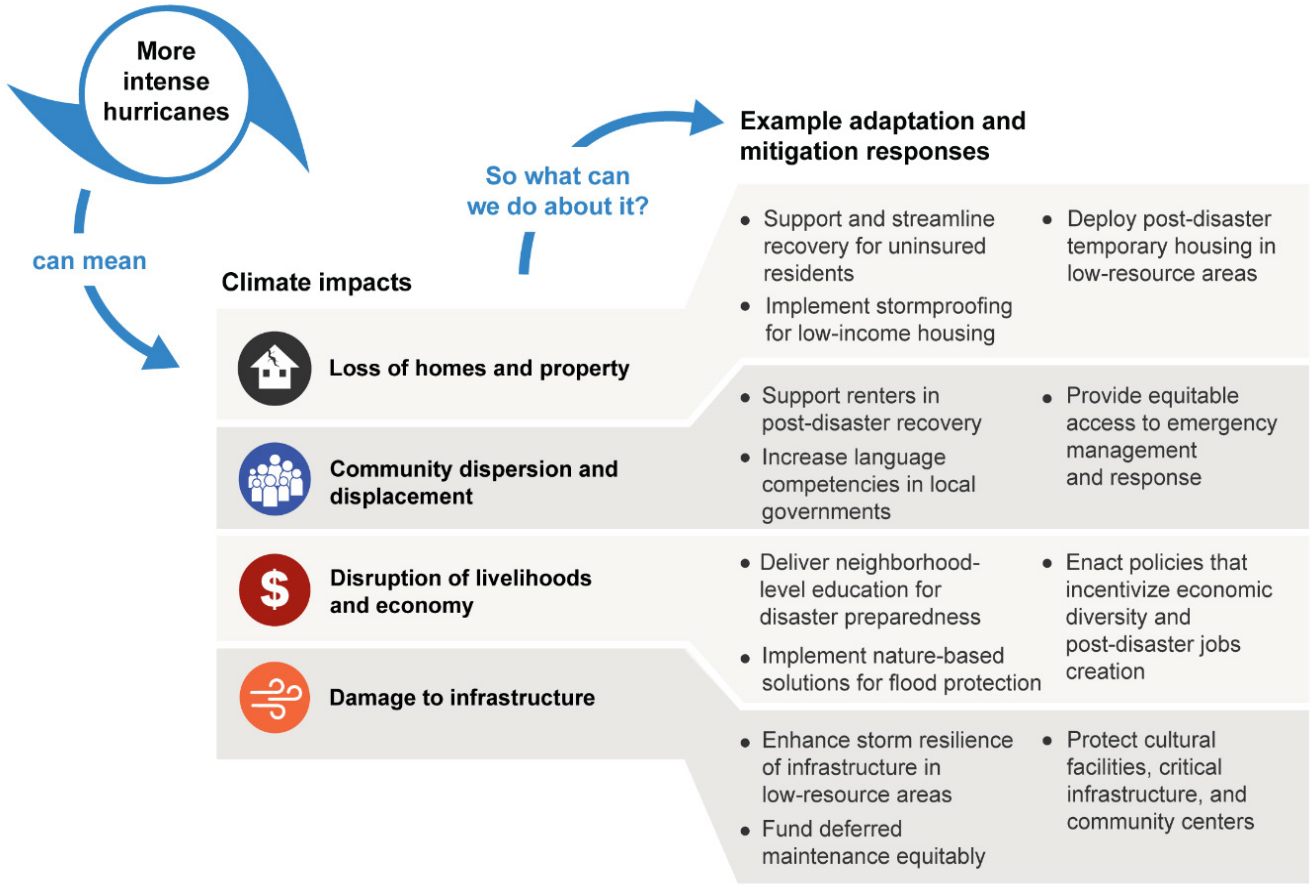
**Nine Tribes of Kansas, Nebraska, and Iowa work together to create customized climate action plans for their individual communities.**

**Figure 26.18.** (**top**) In 2022 Mayetta, Kansas, was the site of a climate resilience workshop for the nine Tribes of Kansas, Nebraska, and Iowa. (**bottom**) Technical teams worked together to create and present specific climate adaptation plans for each Tribe and to share their experiences with one another. Photo credit: ©Mark Junker.

Then the Tribes developed a drought early-warning system for each Tribe. The systems focused on more than 20 drought-related indicators, including precipitation, soil moisture, fire danger indices, and evapotranspiration. Next, the teams wrote summaries of their individual regions' climates in the Winnebago language. They discussed how to communicate local climate change impacts in relevant ways for the people on and near the reservations. The teams also met to create maps showing what areas were projected to be most at risk. By 2022, the groups were sharing how they collected data, analyzed trends, and researched impacts and solutions to climate change on their lands and peoples. The resulting nine climate adaptation plans will strengthen resilience of the Tribes of Kansas, Nebraska, and Iowa for years to come.

Residents, businesses, organizations, and governments in the Southern Great Plains can work together to repair prior societal damage and build community resilience by incorporating justice and equity principles in climate resilience strategies and actions (Figure 26.19).[183] For example, the Resilient El Paso strategy includes social stability, security, and justice among the 12 drivers in its resilience framework.[184] The strategy recognizes El Paso's unique attributes, including one-quarter of El Pasoans living in poverty, a large bilingual population, and its location in the largest binational metroplex in the Western Hemisphere. Development of the strategy involved 70,000 residents participating in 95 community engagement events, ensuring that a range of voices were at the table. These adaptation efforts are complicated, however, by historical trauma, which has diminished trust in government, and the marginalization of various populations (e.g., Norton-Smith et al. 2016[185]).

## Resilience Actions to Address Equity and Justice Issues Related to Increasing Hurricane Risk




**Resilience actions centered on justice and equity can help overburdened communities respond to increasing hurricane risks.**

**Figure 26.19.** More intense hurricanes increase challenges for justice and equity actions across the Southern Great Plains, including loss of homes and property, community dispersion and displacement, disruption of livelihoods and economy, and damage to infrastructure. The example adaptation and mitigation actions can align justice and equity work with climate resilience. Figure credit: See figure metadata for contributors.

## Key Message 26.5

## How We Serve: Climate Change Is Straining Public Infrastructure and Services

The institutions that serve our communities have been challenged to respond and adapt to more frequent and intense weather events (*medium confidence*). Without significant adaptation, climate change is expected to strain water supplies, transportation infrastructure, and emergency services across the Southern Great Plains (*high confidence*). Actions that can enhance our community resilience include substantially reducing greenhouse gas emissions, installing or retrofitting climate-resilient infrastructure, educating students and the public on climate change, and cultivating the capacity of faith- and volunteer-based aid organizations to assist hazard planning, response, and recovery (*medium confidence*).

Communities throughout the Southern Great Plains rely on basic physical infrastructure and public services, from roads and water treatment facilities to healthcare and education. However, the efficiency, effectiveness, and equitable distribution of these fundamental services are being affected by climate change.[186] These services are not available equally across the region. For example, in 2018 along the Texas–Mexico border, only 77% of the Texas *colonia* population had wastewater service.[187] Although *colonia* residents may have access to an electrical connection, many households remain without energy services because of limited income.[188]

Public utilities depend on reliable, safe, and abundant surface water and groundwater. These sources are at risk from increasing air and water temperatures, more frequent and severe drought, more intense rainfall events, and changes in rainfall frequency and timing (Figure 4.2; KM 4.2).[189,190] For example, heavy rainfall events have caused higher concentrations of pollution[191] and more sedimentation in reservoirs.[192] Winter storms have led to the loss of water pressure and electricity at utility facilities (Box 26.2). The average annual number of boil-water notices and sanitary-sewer overflows across Texas increased substantially between 2011 and 2016, mostly because of infrastructure damage following extreme drought that caused clay-soil contraction.[193]

Along the Texas coast, massive water withdrawals from coastal aquifers currently cause most of local sea level rise.[194] Precipitation carrying salt spray remains the major source of brackish waters in the Gulf Coast aquifer, as rising seas have yet to cause significant saltwater intrusion.[195] However, rates of average sea level rise from global warming have accelerated since 1992,[196] and western Gulf Coast sea levels are projected to rise 19–27 inches by 2050 using the full range (low to high) of global mean sea level rise scenarios.[197] The resulting saltwater intrusion is expected to pose challenges for drinking-water suppliers, as costs for desalinating seawater are twice those for brackish groundwater.[195]

The region's transportation systems, including its major airport hubs, ports, and highways, are critical for international and domestic commerce. Transportation infrastructure—much of which is aging and in significant need of repair—has been damaged by extreme weather events associated with climate change (KM 13.1).[198] Extreme heat has reduced passenger and cargo loads for aircraft and buckled roadways and railways; heavy rainfall has eroded road, bridge, and rail foundations (Figure 26.20); and coastal storms have interrupted shipping and caused mass evacuations on roadways. When transportation systems fail, the impacts have been particularly devastating for people living in systematically underserved and under-resourced neighborhoods.[171] As of 2022, Oklahoma's and Texas's state transportation plans do not address threats to transportation services or infrastructure from climate change impacts;[199,200] Kansas's plan does include threats to infrastructure from extreme weather.[201]

## Extreme Rainfall Impacts on Transportation

**Heavy downpours associated with Hurricane Harvey (2017) caused bridge damage.**

**Figure 26.20.** Extreme events associated with climate change are expected to threaten transportation infrastructure, as demonstrated by past experiences. Here, widespread heavy rains associated with Hurricane Harvey (2017) caused the collapse of a section of Farm to Market Road 762 in Fort Bend County, Texas. Photo credit: Kevin Stillman, Texas Department of Transportation.

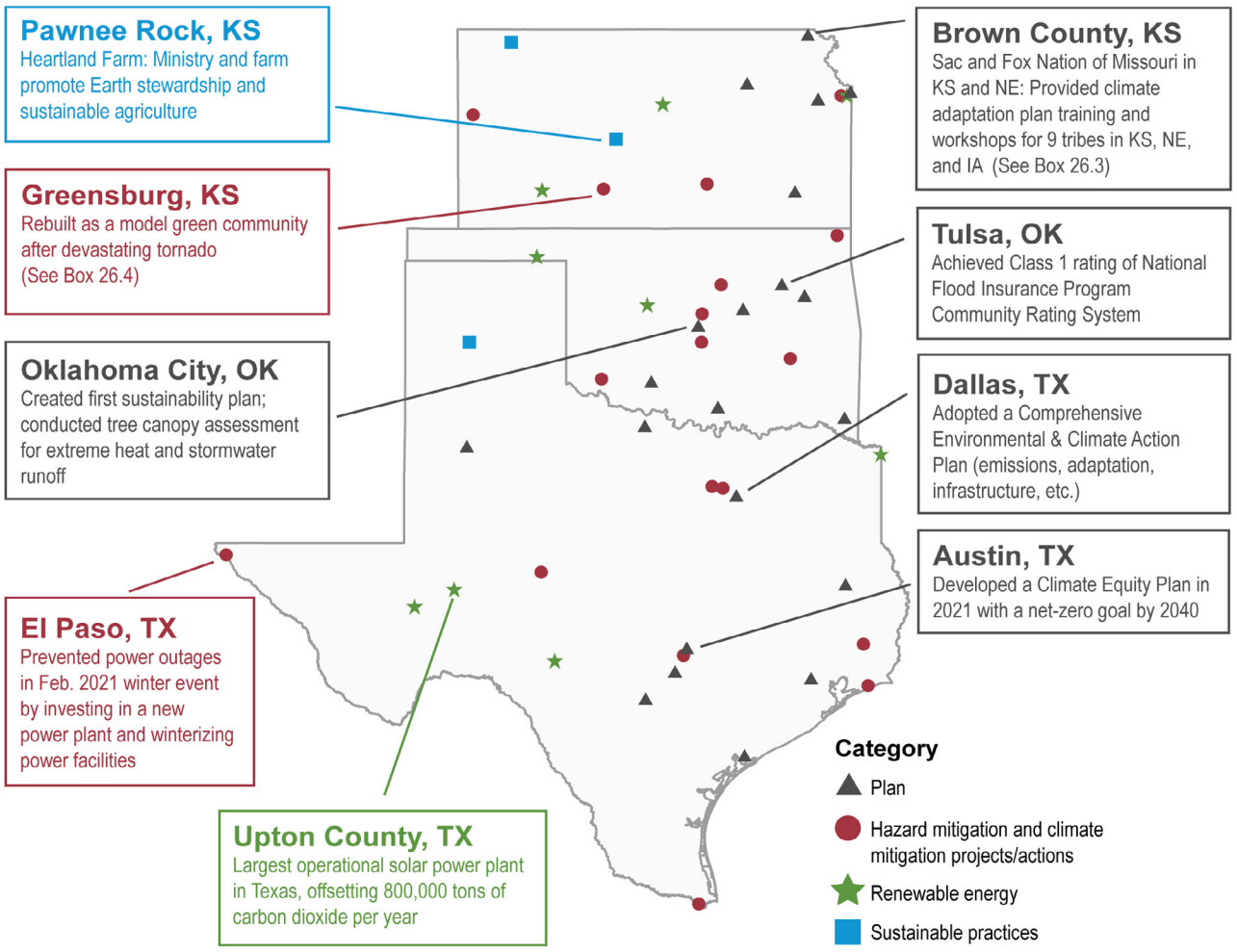
Climate change is also affecting public safety systems and their ability to serve community members. For example, during extreme heat events in 2018, the San Antonio Fire Department received significantly more requests for emergency medical services from neighborhoods with higher rankings on social vulnerability indices.[202] From 2000 to 2018, firefighters in the Southern Great Plains fought 16 megafires—fires that encompass over 100,000 acres, overwhelm local response capacity, and are extinguished only when weather conditions become favorable.[203] These fires are associated with extremely dry vegetation,[204] unusually warm temperatures, and strong winds aloft[203]—conditions projected to become more prevalent as the region warms and soil water evaporates more quickly.

In addition to providing resources for infrastructure, utilities, and public safety, local communities support public education systems. These systems serve learners of all ages and support scientific literacy and social cohesion while serving meals and providing other community services—key steps in enabling public engagement solutions.[205] As of 2022, only Kansas clearly incorporates human-caused climate change in its K–12 state curriculum standards.[206,207,208] Educators rarely receive formal education on the subject, leading many K–12 science teachers to have misconceptions and critical gaps in climate change knowledge. In a survey of teachers and education students in Dallas–Fort Worth,[209] for example, most educators were neutral regarding whether climate scientists disagree about the causes of global warming, even though 97% of these scientists agree (KM 2.1).[210] Informal education programs fill some climate change literacy gaps left by public education through short courses online (e.g., Martin et al. 2020[211]) and Tribal youth education programs.[3] Educators can apply successful strategies for teaching the complexities of climate change by actively engaging learners[212] and infusing lessons with place-based knowledge.[213]

Environmental monitoring and associated data quality assurance and sharing are important to track changes in climate over time, support evidence-based decisions, and warn people of imminent danger. High-resolution, regional weather and water monitoring networks[214,215,216,217] supply critical local measurements for decision-makers. However, understanding local impacts of climate extremes and how to adapt is hampered by a lack of systematic, region-wide observations of species, habitats, economic costs and damages, resource demand and consumption, decision processes, and adaptation and mitigation strategies.[218,219,220,221] Such data would help researchers better understand complex systems and managers develop better local management strategies.

Even without these regional data, cities across the Southern Great Plains are addressing risks to public services through hazard mitigation work and climate adaptation and mitigation actions (Figure 26.21; KM 12.3). Greenburg, Kansas, for example, chose environmentally resilient designs for rebuilding after it was hit by a violent tornado on May 4, 2007 (Box 26.4). In 2020, Oklahoma City produced its first sustainability plan, known as adaptokc, which addressed climate change.[222] Austin, San Antonio, and Dallas also adopted plans that included both mitigation and adaptation actions and have started to address local equity issues as related to climate change impacts (Climate Resilience Action Plan;[223] Climate Ready, Action and Adaptation Plan;[224] and Comprehensive Environmental and Climate Action Plan[225]). Smaller communities that lack resources for stand-alone climate plans are integrating actions into hazard mitigation or comprehensive plans. Results of city actions are becoming evident. For example, in response to frequent flooding that occurred prior to the 1990s, Tulsa enacted flood management actions that resulted in the National Flood Insurance Program awarding Tulsa its highest rating under the Community Rating System, reducing flood insurance premiums by 45%.[226]

## Mitigation and Adaptation Actions Across the Southern Great Plains




**A wide array of actions are being conducted across the region to address the impacts of climate change.**

**Figure 26.21.** Communities and Tribes across the Southern Great Plains are acting in response to the challenges associated with climate variability and change. Actions include developing plans for hazard mitigation, climate action, and climate resilience (black triangles) or undertaking activities related to hazard mitigation (e.g., building resilient infrastructure) and climate mitigation (e.g., reducing energy usage; red circles). Renewable energy projects (green stars) and agricultural or environmental practices that support sustainability (blue squares) are also beginning. For actions under multiple categories, the main category was mapped. These actions aim to increase community resilience to hazards now and in the future. The mapped examples are representative of others occurring elsewhere across the region. See details at https://arcg.is/0yGjKm. Figure credit: See figure metadata for contributors.

The water policies of the three states encourage consumptive use, generally exclude the physical interactions between groundwater and surface waters, and are overseen by multiple agencies across different levels of government. These constraints make water resource solutions difficult in a rapidly changing climate. Nonetheless, Kansas's 2022 statewide water plan includes climate change, its impacts, and associated recommendations, providing a scientifically credible guide for adaptation and mitigation options.[227] The 2012 Oklahoma Comprehensive Water Plan went further by incorporating quantitative climate projections to assess future streamflow, municipal and industrial demand, crop irrigation demand, and water storage.[228] The resulting information was applied in the plan's recommendations. For Texas,

however, the 2022 State Water Plan did not consider climate change.[229] Researchers have spotlighted this crucial omission in Texas's water planning process, especially its lack of planning for droughts worse than the previous record drought.[190]

Communities are beginning to welcome nature-based or green infrastructure solutions for water resource challenges. The City of Austin has implemented water catchment systems, bioswales, and other green infrastructure at libraries, schools, and other city properties to reduce stormwater flows.[230] In Norman, Oklahoma, the Division of Utilities is testing how to augment water supplies during drought by returning highly treated water from its water reclamation facility to a nearby reservoir (Figure 26.22).[231] Cities of all sizes, from Houston (see Box 26.1) to Lenexa, Kansas (population under 50,000),[232] are adopting green infrastructure programs.[233]

## Water Treatment Plant in Norman, Oklahoma

**Wastewater treatment services in the region are addressing water resource challenges.**

**Figure 26.22.** The City of Norman's wastewater treatment facility is testing how to supplement water during drought by returning highly treated water from its water reclamation facility to its nearby reservoir. Water reuse is a well-established adaptation method that is especially useful in semiarid climates. Photo credit: ©City of Norman, Oklahoma.

Faith-based organizations also are responding to climate impacts by raising charitable donations, serving as communication and distribution centers, and recruiting volunteers to assist with both physical and emotional disaster recovery.[234] After Hurricane Harvey (2017), for example, faith communities provided over $242 million (in 2022 dollars) to help flood victims.[235] Interfaith and ecumenical organizations, denominational bodies, local worshipping communities, and individual believers are teaching about climate change and environmental stewardship with their sacred texts or oral traditions[236] and leading environmental actions such as recycling and tree planting.[237] Sharing spiritual beliefs within a local community is an important way to increase social capital for climate adaptation.[238]

## Box 26.4. Building a Sustainable City: Greensburg, Kansas

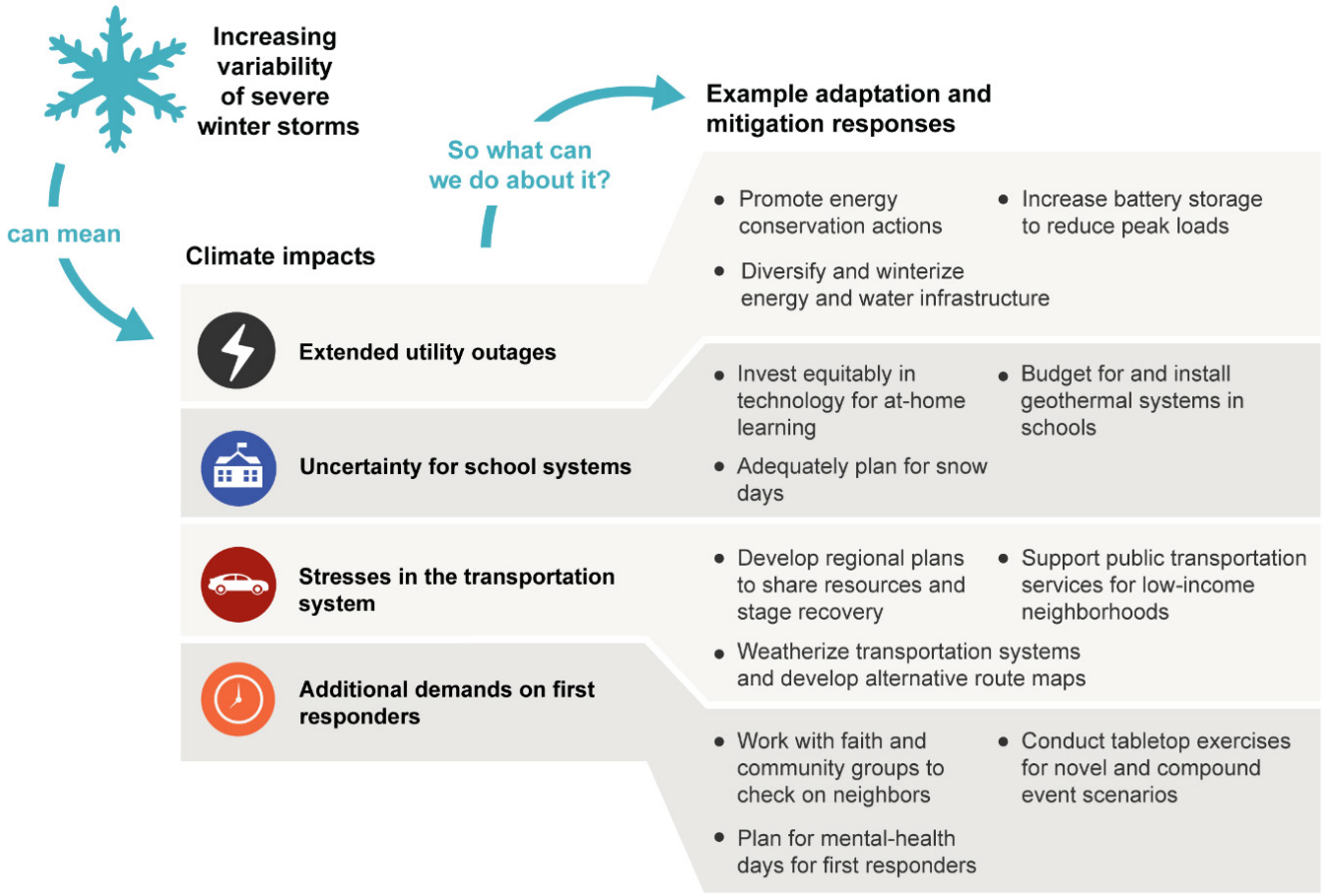
After 90% of the structures in Greensburg, Kansas (population: 1,400), were destroyed by a 2007 tornado, the town's residents rebuilt with an emphasis on resilience and sustainability—elements important to climate change adaptation. The community planned to "green Greensburg" following four visioning meetings that averaged 400 participants each.[239] The resulting 2008 Sustainable Comprehensive Plan reflected their discussions through a focus on children and future generations, a strong community and sustainable economy, and living off and with the land.[240]

Rescoping and rebuilding the city required support from federal, state, university, private, and nonprofit organizations, as well as community groups and individual leaders.[241] The city council provided backing through a resolution requiring that city-owned buildings of 4,000 square feet or larger adhere to "platinum" building standards of the Leadership in Energy and Environmental Design program.[239] This decision led to the creation of a platinum-certified city hall, county school, public hospital, county commons, arts center, and business incubator.[242] Energy-efficient lighting along Main Street reduced energy and maintenance costs; a 10-turbine wind farm generated enough power for 4,000 homes; and native plants, green roofs, and bio-retention areas reduced stormwater runoff.[243] Attracting sustainable businesses to the remote city, however, remains challenging.[241]

During the transformation process, residents' attitudes have changed about sustainability. Many who were initially reluctant found that environmental stewardship was consistent with their values and made common sense, leading them to adopt sustainable practices and technologies for their own homes and landscapes.[243]

Overall, actions in the region have been too slow in pace, and investments have been inadequate in scale and scope, compared to what would be needed[244] to minimize strongly negative consequences of climate change by midcentury (KM 32.1), within the lifetimes of today's young adults. For mitigation, calculations indicate that $CO_2$ emissions would have to decline by about 25% from 2010 levels by 2030 and reach net zero around 2070.[244] While Kansas and Oklahoma reduced carbon emissions 14%–17% between 2010 and 2019, Texas increased emissions by 11%.[245] Transformative adaptation (KM 31.3) and climate equity and justice (KMs 20.1, 20.3) provide holistic frameworks for climate adaptation actions. Many actions that enhance the resilience of public services and infrastructure (Figure 26.23) also are expected to reduce future financial costs from extreme events.

## Resilience Actions to Address the Impacts of Severe Winter Storms on Public Services




**Resilience actions can reduce risks to public services caused by increasingly variable severe winter storms.**

**Figure 26.23.** The increasing variability of severe winter storms causes uncertainty and increases risk in public services and infrastructure across the Southern Great Plains, including extended utility outages, uncertainty for school systems, stresses in the transportation system, and additional demands on first responders. The example adaptation and mitigation actions can increase resilience and reduce negative impacts. Figure credit: See figure metadata for contributors.

# Traceable Accounts

## *Process Description*

The author team for the Southern Great Plains chapter was selected using a standardized rubric on candidate biographies acquired from nominations and an internet search. Rubric elements were 1) subject-matter expertise relevant to the Southern Great Plains; 2) diversity in discipline or type of experience to ensure breadth in chapter content; 3) role that reduced the risk of chapter structural problems, including breadth of perspectives (e.g., gender, ethnicity, race, organization type, career stage, and geographical location); and 4) experience engaging with partners across the region (e.g., government agencies, nongovernmental organizations, practitioners, academics, churches, businesses). Candidate authors were screened by their willingness and ability to work on a team, write well, and commit the necessary time. A few original authors left the team during the Zero Order and First Order Draft stages (either to transfer to another chapter or to address changes in their jobs) and were not replaced.

The author team met virtually for an hour at least biweekly during writing periods to discuss assignments, answer questions, prepare for stakeholder workshops, discuss figures, and reach consensus on topics and written text. The coordinating lead author, chapter lead author, and point of contact met virtually, typically weekly during writing periods, to review due dates, answer questions, and ensure that the team was progressing adequately.

Chapter authors developed initial chapter themes by brainstorming a list of values and interests demonstrated by people living and working across the diverse landscapes of the region. Impact-based statements focused on these values and were clustered by common attributes to reduce redundancy.

Consensus-building occurred through deliberations and by addressing questions during author meetings and through discussions using the comments feature in the shared online draft of the chapter. The lead author checked regularly with the author team for concurrence on any statements drafted by one or more team members. Disagreements on priorities or wording were discussed openly. Confidence was determined through initial, independent assessments of several author team members and finalized after oral discussion during a virtual meeting of the full author team. Concerns were debated until no one disagreed with the stated confidence level. All members of the author team approved of the document for each draft through the Fourth Order Draft. The lead author finalized the Fifth Order Draft, with minimal changes from the Fourth Order Draft, to respond to three minor reviewer comments, suggest copy edits, add missing citations, and address inconsistent figure captions.

The author team chose to hold four 90-minute online stakeholder workshops over two days to provide opportunities for people with different work schedules to participate. Workshops were held at various times of day, including during the noon lunch hour (Central Time) and at 5:30 p.m. for those unable to join during the normal workday. Each workshop began with a 30-minute overview of the full National Climate Assessment (NCA) process and the specific chapter content, followed by six concurrent one-hour breakout sessions—one for each of the five sections of the chapter and one additional session open for any discussion. The author team facilitated the breakout sessions using specific questions to engage participants and obtained feedback through interactive presentations and discussion.

Input from the stakeholder meetings, agency reviews, and internal reviews by the Technical Support Unit (TSU) were addressed through the consensus-building process noted above. The author team discussed content of newly developed graphics during regular meetings and iterated on design with the TSU. Metadata for all graphics and images were collected and documented by the chapter lead author and approved by the TSU. Technical contributors provided specific expertise in the following ways: 1) to alert the author team of local examples of impacts of, adaptation to, or mitigation of climate change; 2) to suggest peer-reviewed

literature in areas where the author team had a disciplinary gap; or 3) to aid in the description of an author-selected figure. Climate projections were available only to 2100; as a result, the author team was not able to assess the impacts of climate change out 100 years, as required by the Global Change Research Act of 1990.[246]

## Key Message 26.1

## How We Live: Climate Change Is Degrading Lands, Waters, Culture, and Health

### Description of Evidence Base

Several topics have an extensive research base both nationwide and within the Southern Great Plains. For these, the author team selected citations that were most relevant for the region. Physical impacts, such as species range shifts, changes in water quality, and stormwater runoff, have sufficient evidence within the region to make well-documented statements (e.g., Howell et al. 2019;[23] Bragg et al. 2003;[24] Moore et al. 2016;[25] Will et al. 2013;[26] Whyte et al. 2021[31]). Literature on human health and climate change was relatively abundant (e.g., Anderegg et al. 2021;[49] Levetin 2021;[50] Neumann et al. 2019;[51] Johnson et al. 2016;[52] Mallen et al. 2019;[53] Bell et al. 2018;[54] Caminade et al. 2019;[56] Raghavan et al. 2021;[57] Hotez 2018;[58] Gorris et al. 2019[59]). The body of literature in climatic regions similar to the Southern Great Plains also supports the statements (e.g., Chs. 6, 8). Studies of human and societal impacts, such as climate impacts to culture, or the intersection of climate and other ecological or human drivers of the system, such as woody encroachment or racial disparities, were more difficult to find. In these cases, the members of the author team used their expert judgment to develop the section text.

Studies for Houston, Dallas, and Austin, Texas, were relatively abundant, as was research on impacts of climate change on both natural ecosystems and agroecosystems in Texas. Research for the case study on Houston was abundant and consistent, although the diversity of peoples and environments across the metropolitan area was extremely broad and had to be condensed in a manner that did not capture the city's nuances to the degree that the authors preferred.

### Major Uncertainties and Research Gaps

Major gaps included lack of research on 1) a wide variety of communities (i.e., the same handful of cities are well documented and others are not), 2) human impacts outside of human morbidity and mortality (e.g., what traditions or cultural practices are changing because of climate change), 3) attribution of climate change to impacts that were driven by multiple stressors (e.g., urban flooding caused by heavier rainfall, changes in land use, and water management practices), and 4) long-term signals of climate change along the Gulf Coast and in Gulf waters (i.e., insufficient observational data over time and space).

There are major uncertainties in individual, family, neighborhood, and community responses to different climate-related impacts, such as higher temperatures, heavier rainfall events, or more intense hurricanes. Adaptation methods are not commonly measured throughout the region, so the circumstances under which different adaptation strategies are most beneficial are highly uncertain (KMs 31.1, 31.3). Although specific Tribes are knowledgeable about climate-related impacts to their relatives and culture, many understandably choose to protect their intellectual property as sovereign nations; thus, some impacts to Tribes are uncertain.

Documentation of impacts and actions for Kansas and Oklahoma was substantially limited in comparison to inland Texas. In fact, peer-reviewed literature focused on or inclusive of Kansas was limited outside of the Kansas City metropolitan area. Literature on changes in waters along the Texas Gulf Coast as related to climate change was sparse, and data sampling was insufficient in space and time to determine long-term

trends in red tide harmful algal blooms, mass mortalities of aquatic organisms (e.g., from cold outbreaks), or freshwater discharge.

### Description of Confidence and Likelihood

For the first statement in the Key Message, the author team had *very high confidence* in risks associated with degradation of lands, waters, and health. However, a lack of data for privately owned areas within the region, notably in Texas, where 93% of land is privately owned,[247] limits the authors' confidence slightly for these areas. The author team had lower confidence in risks associated with quality of life, well-being, and cultural interconnectedness. As a result, the team lowered the confidence level from *very high* to *high*. Confidence in future projections of temperature-related hazards (e.g., extreme heat days) is *very high*; however, confidence is substantially lower (i.e., *medium*) for precipitation-related hazards because projections are mixed on the trends, depending on location. As a result, the team lowered the confidence level from *very high* to *high*. In the third sentence, the author team agreed that all actions were viable and well documented in the literature as resilience activities, but the effectiveness of the actions has not been vetted thoroughly, leading to an assessment of *medium confidence*.

The evidence base was not sufficient to determine quantitative probabilities for the first and third statements in this Key Message; thus, no likelihood is specified. For the second statement, there is sufficient evidence from multiple sources of climate projections across the region to indicate that it is *very likely* that weather hazards will increase (in size, number, or intensity). There also is sufficient evidence in the literature to indicate that these types of changes generally result in negative consequences for human lives, because most US families, neighborhoods, and communities are equipped to handle average climate conditions, but they struggle to be resilient during extremes.

## Key Message 26.2

## How We Work: Climate Changes Are Creating Economic Challenges and Opportunities

### Description of Evidence Base

Impacts of, and mitigations and adaptations for, climate change in the energy and agriculture industries have an extensive research base both nationwide and within the Southern Great Plains (e.g., see Chs. 5, 11; Challinor et al. 2014;[94] Miller et al. 2021;[248] Rojas-Downing et al. 2017;[249] Shoeib et al. 2021;[76] Wimhurst and Greene 2019[77]). For these topics, the author team selected citations that were most relevant for the region. Robust literature was not available for many other businesses and industries across the region. In these cases, the author team selected examples specifically from the region. Research that focused on other regions of the country, even if robust, was not used because the context for resources, culture, and values of the Southern Great Plains differs from other regions of the United States. Thus, the author team chose to respect the place-based nature of impacts and solutions.

Literature on the February 2021 winter storm and its impacts has grown rapidly, and the author team assessed sufficient documentation to discuss the event (e.g., Bolinger et al. 2022;[78] Busby et al. 2021;[86] Doss-Gollin et al. 2021;[250] FERC 2021;[83] Ghosh et al. 2021[84]). Figure 26.8 applied the first, third, and fifth quintiles of the data for both income level (poorest, medium income, wealthiest) and race (low, medium, and high non-White) to demonstrate inequities related to the percentage of power outages during the event.[46] Employment statistics for the fossil fuel industry were calculated for September 2022 using the following categories from the North American Industry Classification System: 211, 2121, 213112, 213113, 22112, 2212, and 3241.[73]

The literature on topics such as geothermal energy production and carbon capture and storage has grown in academic and federal government publications; however, commercial-scale implementation of these technologies was considered of more interest to the chapter audience even though the literature was scarce.

### Major Uncertainties and Research Gaps

In addition to government services (KM 26.5), energy, and agriculture, major economic sectors in the region that may be affected by climate change include manufacturing, retail services, construction, hospitality, real estate, insurance, wholesale trade, and social assistance. Little to no peer-reviewed literature was found related to impacts, adaptation, or mitigation for these sectors.

As in other sections, literature was substantially sparser for Kansas and Oklahoma than for Texas. Most of the literature on climate-change impacts and actions related to business and industry, except for agriculture, was focused on major metropolitan areas; thus, rural areas were less studied. The literature on climate impacts to women- or minority-owned businesses or small businesses in the region was minimal. Research was limited on adaptation and mitigation actions in the region, including the evaluation of their effectiveness.

Peer-reviewed literature on the impacts of the February 2021 winter storm was limited except for the storm's impact on energy generation, transmission, and distribution. News articles discussed a wide range of other impacts, from transportation and the economy to recreation and mental health, but few studies analyzing non-energy impacts were available in the literature at the time of writing.

### Description of Confidence and Likelihood

In the first statement for the Key Message, the author team determined that the literature was limited regarding how business and industry experience new employment opportunities as climate conditions change across the Southern Great Plains. Thus, the author team lowered the confidence level from *very high* (i.e., the level that would be assigned to the US as a whole) to *high* (for the Southern Great Plains region). For the second statement, confidence was assessed as *high* based on substantial evidence from available climate projections but less evidence for costs to businesses and industry. For the third statement, the literature was thin with respect to how actions by business and industry result in positive economic outcomes; hence, the team concluded that *medium confidence* was most appropriate.

The evidence base was not sufficient to determine quantitative probabilities for the first and third statements in this Key Message; thus, no likelihood is specified. For the second statement, there is sufficient evidence from multiple sources of climate projections to indicate that it is *very likely* that warmer temperatures, more erratic precipitation, and sea level rise will occur across the region in the future. These types of changes are linked to costs and losses in business and industry.

## Key Message 26.3

## How We Play: Climate Extremes Are Endangering Sports, Recreation, and Leisure

### Description of Evidence Base

The author team considered the topic of climate change and sports (i.e., sports ecology) to be an emerging area that will be of great interest to readers in the Southern Great Plains. Discussion about climate change and organized sport, from youth to professional, has been limited in prior NCAs. Yet the literature on how

climate affects health outcomes in sports and other physical activities has been growing (e.g., Bernard et al. 2021;[120] Bergeron et al. 2011;[130] Yeargin et al. 2017;[127] Vanos et al. 2017;[132] Orr et al. 2022;[118] Thomas et al. 2013;[141] Brocherie et al. 2015[122]). The lack of access to parks is a major theme in environmental justice and public health literature (e.g., Heynen et al. 2006;[251] Sister et al. 2010;[252] Rigolon 2016;[134] Mullenbach and Wilhelm Stanis 2022[253]). Negative impacts of climate change on ecosystem services, including hunting, fishing, and other types of recreation, also are well documented (KM 8.3); however, positive impacts are less studied. Studies in the Southern Great Plains are abundant on health outcomes and ecosystem services in the face of climate change.

Literature on the economic impacts of specific extreme events on recreation can be found, especially for Texas, but comprehensive literature on these impacts across the region or across recreation, sports, and leisure does not exist. In these cases, the author team gave examples from specific activities, events, and locations from the literature or provided examples from multiple news reports. As in other sections, peer-reviewed literature related to this section was most abundant for Texas, especially the Texas Gulf Coast, and least abundant for Kansas. Although examples were available for specific adaptation actions, literature evaluating the effectiveness of these actions was limited.

## Major Uncertainties and Research Gaps

Documentation of how climate change affected the amount, timing, and intensity of physical activity on a community or larger scale is limited. Prior research focused primarily on the impacts of climate on football players. Research remains lacking on the impacts on other sports (e.g., soccer, lacrosse, cross-country). Comparative studies across the region are rare for impacts of climate change on sports, recreation, and leisure activities. Literature regarding climate change impacts and adaptation actions for recreational activities in Texas Gulf waters is minimal.

Research is limited on the convergence of environmental justice, climate, and sports and recreation, especially among Indigenous communities and in rural settings. Economic impact studies tend to focus on singular extreme events in limited regions and thus do not provide a comprehensive understanding from state to state, activity to activity, or sport to sport. Research is limited on the climate adaptations of sports organizations to reduce climate vulnerabilities, as well as on the outcomes (positive or negative) of those adaptations.

## Description of Confidence and Likelihood

Peer-reviewed literature was abundant and consistent, leading the author team to an assessment of *very high confidence* for the first statement in the Key Message. The other two statements were assessed at *high confidence* based on a smaller evidence base on climate change impacts on reduction of outdoor physical activity and on the types of adaptation strategies used by individuals, communities, or sport organizations.

The evidence base was not sufficient to determine quantitative probabilities for the first and third statements in this Key Message; thus, no likelihood was specified. For the second statement, there was sufficient evidence from multiple sources of climate projections to indicate that it is *very likely* that heat extremes will increase across the region in the future. The literature is sufficient to recognize that heat extremes are linked to heat-related illness and death and that they also result in a reduction of outdoor physical activity.

## Key Message 26.4

## How We Heal: Climate Change Is Exacerbating Existing Social and Environmental Disparities

### Description of Evidence Base

Social science literature regarding justice and equity as related to climate hazards was abundant and consistent, especially as related to extreme heat, flooding, and tropical cyclones (e.g., Benevolenza and DeRigne 2019;[68] Flores et al. 2021;[254] Maldonado et al. 2016;[255] Prudent et al. 2016;[256] Smiley et al. 2022[257]). Research on low-income communities and communities of color was extensive for many metropolitan and industrial areas in the region (e.g., Collins et al. 2019,[258] 2013;[259] Flores et al. 2021;[254] Li et al. 2022[260]). There is a cluster of research on tropical cyclones, sea level rise, and infrastructural disparities in marginalized communities in Texas coastal metropolitan and industrial areas, with some studies focusing on South Texas, where many *colonias* are located (e.g., Atisa and Racelis 2022;[261] Martinich et al. 2013;[160] Flores et al. 2021;[254] Chakraborty et al. 2019[169]). The *Status of Tribes and Climate Change Report*[3] provided extensive examples and documentation of challenges and opportunities, and it was useful for content and context across the entire chapter. Evidence-based solutions were limited, especially those over a sufficient time period to evaluate long-term effectiveness.

### Major Uncertainties and Research Gaps

In comparison to research on the physical impacts of climate change, there is significantly less research in the Southern Great Plains on climate change through the lens of justice and equity. Those most impacted include people and families with low incomes; rural residents; historically marginalized populations; disabled persons; older adults; Black, Indigenous and People of Color; those who do not identify as cis, straight male; immigrants; those living in *colonias*; and unhoused individuals; however, the author team found no studies that analyze the impacts on these populations systematically across any of the three states. In addition, although there are several studies assessing challenges for Spanish-speaking individuals, those who speak other non-English languages generally are not included. In some cases, literature diagnoses disparities without explaining the reasons for them (e.g., Carvallo et al. 2021[85]), indicating that additional research is needed to analyze the root causes so that they can be addressed alongside climate adaptation and mitigation actions (i.e., to avoid maladaptation; KM 31.4).

Peer-reviewed research has tended to focus on cities, with less emphasis on rural communities or small- to medium-sized cities in the region. Even for locations near the Southern Great Plains, there is little literature on climate justice as it relates to rural communities (e.g., Gutierrez and LePrevost 2016[262]). Knowledge is limited regarding the evaluation of climate mitigation and adaptation strategies that seek to incorporate climate justice and equity (e.g., Mullenbach and Wilhelm Stanis 2022[253]). Because of their sovereignty, Tribes have chosen, in many circumstances, to document their work through oral traditions, which are not shared with outsiders.[3]

### Description of Confidence and Likelihood

Based on the abundance of research and consistency of results across the US and within the region, the author team assessed the first two Key Message statements with *very high confidence*. How the specific demographics or location of the neighborhoods and communities relate to a higher risk of impacts remains to be studied more completely, but the first two statements were intentionally general to highlight what is known from the literature. The third statement was assessed with *medium confidence* because rigorous evaluation of outcomes from policies, practices, and programs is more limited in the literature.

Although the literature is compelling for many of the physical impacts of climate change, impacts to individuals, neighborhoods, and communities were not as robustly documented and certainly did not cover the entire region. Hence, no likelihood is specified for any statement, as the author team could not assess quantitative probabilities through case studies or analyses of small regions within the Southern Great Plains.

## Key Message 26.5

## How We Serve: Climate Change Is Straining Public Infrastructure and Services

### Description of Evidence Base

Public infrastructure and services topics related to water supply (KM 4.2), infrastructure (KMs 12.2, 13.1), public health and safety (KM 15.1), and education[212] had an extensive research base nationwide and across specific regions of the United States. Research in the Southern Great Plains was less robust. In this case, the authors, many of whom have worked for or with municipalities across the region for decades, used their expert judgment to communicate the message and to select the most relevant citations. Other evidence for this Key Message included state water plans,[227,247,263] state transportation plans,[199,200,201] and state science curriculum standards[207,208,264] for each of the three states.

Scholarship is abundant regarding agricultural water needs and uses across the Southern Great Plains; however, peer-reviewed literature regarding climate change and municipal water supplies or water sustainability was sparse for all three states. How climate change affects public infrastructure and services in the region is an emerging topic, with much of the research done only in the past decade. News media covered local impacts after extreme events, including the damage to public infrastructure and response by service agencies and organizations. Because cities and towns are important locations where climate mitigation and adaptation occur, the author team chose to cover this topic even though the evidence base was smaller than that for the other sections.

In addition, the author team chose to discuss the emergent topic of the role of faith-based organizations, as it was well aligned with values in the region. These organizations also can use content in this report to plan for community service before, during, and after climate hazards. Although major religions have statements regarding climate change (e.g., *Laudato si'* encyclical from Pope Francis, "Islamic Declaration on Climate Change," "Buddhist Climate Change Statement to World Leaders," and "Interfaith Climate Statement"),[265] literature regarding the interactions of faith, religion, and climate change is limited.[238,266] Peer-reviewed literature was sparse on how faith-based organizations conduct adaptation or mitigation actions or the scope and effectiveness of these activities.

Information about what actions communities were taking in the region was primarily documented in state or municipal reports rather than the peer-reviewed literature (e.g., City of San Antonio 2019;[224] City of Oklahoma City 2020[222]). Hence, no evaluation of the effectiveness of or public support for the actions was available. State transportation plans did not have detailed articulation of threats to transportation services or infrastructure as related to climate change. The 2020–2045 Kansas Long Range Transportation Plan;[201] Oklahoma Long Range Transportation Plan: 2020–2045;[199] and the Texas Transportation Plan 2050[200] did not provide goals or objectives that addressed climate-change impacts. Although Kansas and Oklahoma acknowledged the need to support electric-vehicle charging stations, climate-change adaptation and mitigation were minimal elements of these plans and provided little context for the author team. For water resources management, significant content was available in the 2022 Kansas Water Plan[227] and the 2012 Oklahoma Comprehensive Water Plan.[263] Conversely, the Texas Water Development Board[229] did not

acknowledge climate change or plan for its impacts on water resources management, thus limiting the content for Texas.

## Major Uncertainties and Research Gaps

Data for and analyses of climate change impacts on public services and infrastructure in the region were sporadic, even though research, data, and projections for temperature, precipitation, and other physical climate indicators over land were generally plentiful. Also, although coastal and offshore data were available for the Gulf of Mexico from the Gulf of Mexico Coastal Ocean Observing System[267] and Texas Automated Buoy System,[268] these observing systems were not established to monitor long-term climate trends (e.g., ocean acidification, saltwater intrusion), and thus there was a scarcity of literature on how these observing systems aided decision support for climate change.

Few studies on public infrastructure and services focused on Kansas and Oklahoma, with most research in Texas. Of those on Kansas and Oklahoma, many were decades old. For all states, most studies examined specific facilities or communities; there were few synthesis or comparison studies that helped present a larger picture of climate change impacts across the region. Documentation of how climate change is projected to affect the healthcare system or healthcare facilities was sparse, although research on climate change and public health was relatively abundant (see Traceable Account for KM 26.1). Similarly, broad syntheses across the region of the impacts of climate change on roadways, railways, ports, pipelines, and airports, or the reliability and safety of transportation systems, were unavailable. In addition, with the region's residents and visitors heavily dependent on automobiles and trucks, there was a large gap in the research on what mitigation and adaptation measures were recommended for moving into a next-generation, climate-smart transportation system.

Few peer-reviewed publications existed, specific to the region, regarding the intersection of public safety and climate change, including current planning processes, effective adaptation, and economic costs. The documentation available primarily focused on historical events and rarely on projections into the future. Similarly, information was minimal regarding how climate change was incorporated into the curriculum at various education levels across all three states, whether in formal or informal programs.

Even though faith-based organizations play significant roles locally, regionally, and globally when crises occur, most of the literature on climate change and faith focused on individual knowledge, opinions, or actions based on religious affiliation. The scope of what these organizations were doing (or not doing) and how they were accomplishing their works were unclear.

## Description of Confidence and Likelihood

Confidence was assessed to be *medium* for the first statement, which was the consensus after acknowledging both the dearth of peer-reviewed literature (which would have led to *low confidence*) and the experience of members of the author team who served one or more communities and networked with others who do the same (which would have led to *high confidence*). In this case, much of the work being conducted across the region is relatively recent (e.g., since the publication of NCA4 in 2018); thus, ongoing research has yet to reach publication stage. For the second statement, the *high confidence* level was chosen primarily because of the authors' knowledge of the climate projections and those events that have most affected public infrastructure and services in the past. As with other sections, evaluation of mitigation and adaptation options in the region is sparse (KM 31.1). The effectiveness of solutions is generally place-based, so the author team chose *medium confidence* based on these uncertainties.

Although climate projections indicate that more frequent and intense climate-related events are *very likely* in the future for the region, the author team did not find sufficient literature on the reliability, cost, and

distribution of community services to generate quantitative probabilities of likelihood. Thus, no likelihood is specified for any statement in the Key Message.

# References


1. EPA, 2013: Level III Ecoregions of the Continental United States. U.S. Environmental Protection Agency, National Health and Environmental Effects Research Laboratory. https://gaftp.epa.gov/epadatacommons/ord/ecoregions/us/eco_level_iii_us.pdf

2. IPBES, 2019: *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Díaz, S., J. Settele, E.S. Brondízio, H.T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K.A. Brauman, S.H.M. Butchart, K.M.A. Chan, L.A. Garibaldi, K. Ichii, J. Liu, S.M. Subramanian, G.F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y.J. Shin, I.J. Visseren-Hamakers, K.J. Willis, and C.N. Zayas, Eds. IPBES Secretariat, Bonn, Germany, 56 pp. https://www.ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf

3. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

4. Lavin, S.J., F.M. Shelley, and J.C. Archer, 2011: *Atlas of the Great Plains*. University of Nebraska Press, 352 pp. https://www.nebraskapress.unl.edu/nebraska/9780803215368/

5. Collins, S.D., L.J. Heintzman, S.M. Starr, C.K. Wright, G.M. Henebry, and N.E. McIntyre, 2014: Hydrological dynamics of temporary wetlands in the southern Great Plains as a function of surrounding land use. *Journal of Arid Environments*, **109**, 6–14. https://doi.org/10.1016/j.jaridenv.2014.05.006

6. Matthews, W.J., C.C. Vaughn, K.B. Gido, and E. Marsh-Matthews, 2005: Ch. 7. Southern Plains rivers. In: *Rivers of North America*. Benke, A.C. and C.E. Cushing, Eds. Academic Press, Burlington, MA, 282–325. https://doi.org/10.1016/b978-012088253-3/50010-9

7. Lovelace, J.K., M.G. Nielsen, A.L. Read, C.J. Murphy, and M.A. Maupin, 2020: Estimated Groundwater Withdrawals from Principal Aquifers in the United States, 2015. Circular 1464. U.S. Geological Survey, Reston, VA, 70 pp. https://doi.org/10.3133/cir1464

8. Costigan, K.H. and M.D. Daniels, 2012: Damming the prairie: Human alteration of Great Plains river regimes. *Journal of Hydrology*, **444-445**, 90–99. https://doi.org/10.1016/j.jhydrol.2012.04.008

9. Heidari, H., M. Arabi, and T. Warziniack, 2021: Vulnerability to water shortage under current and future water supply-demand conditions across U.S. river basins. *Earth's Future*, **9** (10), 2021EF002278. https://doi.org/10.1029/2021ef002278

10. EIA, 2020: Map of Fossil Fuel Resources in the U.S. U.S. Energy Information Administration. https://atlas.eia.gov/apps/fossil-fuels/explore

11. EIA. 2022: Electricity: Capacity of Electric Power Plants, Annual: Existing Capacity by Energy Source, by Producer, by State Back to 2000 (Annual Data From the EIA-860). U.S. Energy Information Administration. https://www.eia.gov/electricity/data.php

12. Frankson, R., K.E. Kunkel, L.E. Stevens, D.R. Easterling, X. Lin, M. Shulski, N.A. Umphlett, and C.J. Stiles, 2022: Kansas State Climate Summary 2022. NOAA Technical Report NESDIS 150-KS. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/ks/

13. Runkle, J., K.E. Kunkel, J. Nielson-Gammon, R. Frankson, S.M. Champion, B.C. Stewart, L. Romolo, and W. Sweet, 2022: Texas State Climate Summary 2022. NOAA Technical Report NESDIS 150-TX. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD, 5 pp. https://statesummaries.ncics.org/chapter/tx/

14. Frankson, R., K.E. Kunkel, L.E. Stevens, S.M. Champion, B.C. Stewart, and J. Nielsen-Gammon, 2022: Oklahoma State Climate Summary 2022. NOAA Technical Report NESDIS 150-OK. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/ok/

15. Kirchmeier-Young, M.C. and X. Zhang, 2020: Human influence has intensified extreme precipitation in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (24), 13308–13313. https://doi.org/10.1073/pnas.1921628117

16. NDMC, 2023: U.S. Drought Monitor: Data Tables. University of Nebraska-Lincoln, National Drought Mitigation Center, Lincoln, NE, accessed May 21, 2023. https://droughtmonitor.unl.edu/dmdata/datatables.aspx

17. NCEI, 2023: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

18. EIA, 2023: Electricity Data Browser. U.S. Energy Information Administration, accessed May 3, 2023. https://www.eia.gov/electricity/data/browser/

19. EPA, 2023: Greenhouse Gas Inventory Data Explorer. U.S. Environmental Protection Agency, Washington, DC, accessed May 26, 2023. https://cfpub.epa.gov/ghgdata/inventoryexplorer/index.html#allsectors/allsectors/allgas/gas/all

20. Ansley, R.J., V.H. Rivera-Monroy, K. Griffis-Kyle, B. Hoagland, A. Emert, T. Fagin, S.R. Loss, H.R. McCarthy, N.G. Smith, and E.F. Waring, 2023: Assessing impacts of climate change on selected foundation species and ecosystem services in the South-Central USA. *Ecosphere*, **14** (2), e4412. https://doi.org/10.1002/ecs2.4412

21. Archer, S.R., E.M. Andersen, K.I. Predick, S. Schwinning, R.J. Steidl, and S.R. Woods, 2017: Ch. 2. Woody plant encroachment: Causes and consequences. In: *Rangeland Systems: Processes, Management and Challenges*. Briske, D.D., Ed. Springer, Cham, Switzerland, 25–84. https://doi.org/10.1007/978-3-319-46709-2_2

22. Twidwell, D., W.E. Rogers, S.D. Fuhlendorf, C.L. Wonkka, D.M. Engle, J.R. Weir, U.P. Kreuter, and C.A. Taylor, Jr., 2013: The rising Great Plains fire campaign: Citizens' response to woody plant encroachment. *Frontiers in Ecology and the Environment*, **11** (s1), 64–71. https://doi.org/10.1890/130015

23. Howell, N.L., E.B. Butler, and B. Guerrero, 2019: Water quality variation with storm runoff and evaporation in playa wetlands. *Science of The Total Environment*, **652**, 583–592. https://doi.org/10.1016/j.scitotenv.2018.10.298

24. Bragg, D.C., M.G. Shelton, and B. Zeide, 2003: Impacts and management implications of ice storms on forests in the southern United States. *Forest Ecology and Management*, **186** (1), 99–123. https://doi.org/10.1016/s0378-1127(03)00230-5

25. Moore, G.W., C.B. Edgar, J.G. Vogel, R.A. Washington-Allen, Rosaleen G. March, and R. Zehnder, 2016: Tree mortality from an exceptional drought spanning mesic to semiarid ecoregions. *Ecological Applications*, **26** (2), 602–611. https://doi.org/10.1890/15-0330

26. Will, R.E., S.M. Wilson, C.B. Zou, and T.C. Hennessey, 2013: Increased vapor pressure deficit due to higher temperature leads to greater transpiration and faster mortality during drought for tree seedlings common to the forest-grassland ecotone. *New Phytologist*, **200** (2), 366–374. https://doi.org/10.1111/nph.12321

27. Zhang, W., G. Villarini, G.A. Vecchi, and J.A. Smith, 2018: Urbanization exacerbated the rainfall and flooding caused by Hurricane Harvey in Houston. *Nature*, **563** (7731), 384–388. https://doi.org/10.1038/s41586-018-0676-z

28. Texas GLO, 2019: Texas Coastal Resiliency Plan. Texas General Land Office. https://coastalstudy.texas.gov/resources/files/2019-coastal-master-plan.pdf

29. Cozzetto, K., K. Chief, K. Dittmer, M. Brubaker, R. Gough, K. Souza, F. Ettawageshik, S. Wotkyns, S. Opitz-Stapleton, S. Duren, and P. Chavan, 2014: Ch. 6. Climate change impacts on the water resources of American Indians and Alaska Natives in the U.S. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., R.E. Pandya, and B.J. Colombi, Eds. Springer, Cham, Switzerland, 61–76. https://doi.org/10.1007/978-3-319-05266-3_6

30. Pearson, J., G. Jackson, and K.E. McNamara, 2023: Climate-driven losses to Indigenous and local knowledge and cultural heritage. *The Anthropocene Review*, **10** (2), 343–366. https://doi.org/10.1177/20530196211005482

31. Whyte, K., C. Avery, E. Azzuz, J. Breckinridge, C. Cooley, K. Cozzetto, R. Croll, M. Cruz, P. Ezcurra, P. Hardison, C. Jones, F. Lake, C. Magee, D.M. Marks-Marino, D., H. Mullen, C. Nelson, A. Pairis, H. Panci, B. Rodriguez, H. Sorensen, C. Spriggs, and A. Warneke, 2021: Ch. 4. Ecosystems & biodiversity. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 56–80. http://nau.edu/stacc2021

32. Reeder-Myers, L.A. and M.D. McCoy, 2019: Preparing for the future impacts of megastorms on archaeological sites: An evaluation of flooding from Hurricane Harvey, Houston, Texas. *American Antiquity*, **84** (2), 292–301. https://doi.org/10.1017/aaq.2018.85

33. Berlemann, M. and M.F. Steinhardt, 2017: Climate change, natural disasters, and migration—A survey of the empirical evidence. *CESifo Economic Studies*, **63** (4), 353–385. https://doi.org/10.1093/cesifo/ifx019

34. Chort, I. and M. de la Rupelle, 2022: Managing the impact of climate on migration: Evidence from Mexico. *Journal of Population Economics*, **35** (4), 1777–1819. https://doi.org/10.1007/s00148-022-00894-1

35. McLeman, R.A., J. Dupre, L. Berrang Ford, J. Ford, K. Gajewski, and G. Marchildon, 2014: What we learned from the Dust Bowl: Lessons in science, policy, and adaptation. *Population and Environment*, **35** (4), 417–440. https://doi.org/10.1007/s11111-013-0190-z

36. Shen, X., C. Cai, Q. Yang, E.N. Anagnostou, and H. Li, 2021: The US COVID-19 pandemic in the flood season. *Science of The Total Environment*, **755**, 142634. https://doi.org/10.1016/j.scitotenv.2020.142634

37. Coffey, R., M.J. Paul, J. Stamp, A. Hamilton, and T. Johnson, 2019: A review of water quality responses to air temperature and precipitation changes 2: Nutrients, algal blooms, sediment, pathogens. *JAWRA Journal of the American Water Resources Association*, **55** (4), 844–868. https://doi.org/10.1111/1752-1688.12711

38. Schlinger, C., O. Conroy-Ben, C. Cooley, N. Cooley, M. Cruz, D. Dotson, J. Doyle, M.J. Eggers, P. Hardison, M. Hatch, C. Hogue, K. Jacobson Hedin, C. Jones, K. Lanphier, D. Marks-Marino, D. Mosley, F. Olsen Jr., and M. Peacock, 2021: Ch. 4.2. Water. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 98–141. http://nau.edu/stacc2021

39. U.S. Census Bureau, 2020: City and Town Population Totals: 2010-2020. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/programs-surveys/popest/technical-documentation/research/evaluation-estimates/2020-evaluation-estimates/2010s-cities-and-towns-total.html

40. U.S. Census Bureau. 2021: Annual Estimates of the Resident Population for Metropolitan Statistical Areas in the United States and Puerto Rico: April 1, 2020 to July 1, 2021. U.S. Department of Commerce, U.S. Census Bureau. https://www2.census.gov/programs-surveys/popest/tables/2020-2021/metro/totals/cbsa-met-est2021-pop.xlsx

41. Muir, A.F., 1943: The destiny of Buffalo Bayou. *The Southwestern Historical Quarterly*, **47** (2), 91–106. https://www.jstor.org/stable/30236015

42. Feagin, J.R., 1997: *The New Urban Paradigm: Critical Perspectives on the City*. Rowman & Littlefield, 384 pp. https://rowman.com/isbn/9780847684991/the-new-urban-paradigm-critical-perspectives-on-the-city

43. U.S. Census Bureau, 2020: American Community Survey (ACS). U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/programs-surveys/acs

44. Klineberg, S.L., R. Bozick, and Kinder Institute for Urban Research, 2021: The Fortieth Year of the Kinder Houston Area Survey: Into the Post-Pandemic Future. Rice University, Kinder Institute for Urban Research, Houston, TX. https://doi.org/10.25611/hz81-gt44

45. Hayden, M.H., O.V. Wilhelmi, D. Banerjee, T. Greasby, J.L. Cavanaugh, V. Nepal, J. Boehnert, S. Sain, C.Burghardt, and S. Gower, 2017: Adaptive capacity to extreme heat: Results from a household survey in Houston, Texas. *Weather, Climate, and Society*, **9** (4), 787–799. https://doi.org/10.1175/wcas-d-16-0125.1

46. Rice University Kinder Institute for Urban Research, 2022: Harris County Winter Storm Uri Resilience Assessment in Harris County. Rice University, Kinder Institute for Urban Research, Houston, TX. https://doi.org/10.25611/yt6s-k856

47. City of Houston, 2020: Resilient Houston. City of Houston. https://www.houstontx.gov/mayor/Resilient-Houston-20200518-single-page.pdf

48. Stoner, A. and K. Hayhoe, 2020: Climate Impact Assessment for the City of Houston. ATMOS Research and Consulting, 69 pp. https://www.houstontx.gov/mayor/Climate-Impact-Assessment-2020-August.pdf

49. Anderegg, W.R.L., J.T. Abatzoglou, L.D.L. Anderegg, L. Bielory, P.L. Kinney, and L. Ziska, 2021: Anthropogenic climate change is worsening North American pollen seasons. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (7), e2013284118. https://doi.org/10.1073/pnas.2013284118

50. Levetin, E., 2021: Aeroallergens and climate change in Tulsa, Oklahoma: Long-term trends in the south central United States. *Frontiers in Allergy*, **2**, 726445. https://doi.org/10.3389/falgy.2021.726445

51. Neumann, J.E., S.C. Anenberg, K.R. Weinberger, M. Amend, S. Gulati, A. Crimmins, H. Roman, N. Fann, and P.L. Kinney, 2019: Estimates of present and future asthma emergency department visits associated with exposure to oak, birch, and grass pollen in the United States. *GeoHealth*, **3** (1), 11–27. https://doi.org/10.1029/2018gh000153

52. Johnson, M.G., S. Brown, P. Archer, A. Wendelboe, S. Magzamen, and K.K. Bradley, 2016: Identifying heat-related deaths by using medical examiner and vital statistics data: Surveillance analysis and descriptive epidemiology—Oklahoma, 1990–2011. *Environmental Research*, **150**, 30–37. https://doi.org/10.1016/j.envres.2016.05.035

53. Mallen, E., B. Stone, and K. Lanza, 2019: A methodological assessment of extreme heat mortality modeling and heat vulnerability mapping in Dallas, Texas. *Urban Climate*, **30**, 100528. https://doi.org/10.1016/j.uclim.2019.100528

54. Bell, J.E., C.L. Brown, K. Conlon, S. Herring, K.E. Kunkel, J. Lawrimore, G. Luber, C. Schreck, A. Smith, and C. Uejio, 2018: Changes in extreme events and the potential impacts on human health. *Journal of the Air & Waste Management Association*, **68** (4), 265–287. https://doi.org/10.1080/10962247.2017.1401017

55. EPA, 2023: Texas Nonattainment/Maintenance Status for Each County by Year for All Criteria Pollutants. U.S. Environmental Protection Agency, accessed May 21, 2023. https://www3.epa.gov/airquality/greenbook/anayo_tx.html

56. Caminade, C., K.M. McIntyre, and A.E. Jones, 2019: Impact of recent and future climate change on vector-borne diseases. *Annals of the New York Academy of Sciences*, **1436** (1), 157–173. https://doi.org/10.1111/nyas.13950

57. Raghavan, R.K., Z.L. Koestel, G. Boorgula, A. Hroobi, R. Ganta, J. Harrington, Jr., D. Goodin, R.W. Stich, and G. Anderson, 2021: Unexpected winter questing activity of ticks in the central Midwestern United States. *PLoS ONE*, **16** (11), e0259769. https://doi.org/10.1371/journal.pone.0259769

58. Hotez, P.J., 2018: The rise of neglected tropical diseases in the "new Texas". *PLoS Neglected Tropical Diseases*, **12** (1), e0005581. https://doi.org/10.1371/journal.pntd.0005581

59. Gorris, M.E., K.K. Treseder, C.S. Zender, and J.T. Randerson, 2019: Expansion of coccidioidomycosis endemic regions in the United States in response to climate change. *GeoHealth*, **3** (10), 308–327. https://doi.org/10.1029/2019gh000209

60. Peterson, C., V. Chu, J. Lovelace, M. Almekdash, and M. Lacy, 2022: Coccidioidomycosis cases at a regional referral center, West Texas, USA, 2013–2019. *Emerging Infectious Diseases*, **28** (4), 848–851. https://doi.org/10.3201/eid2804.211912

61. Davey Resource Group, 2019: Oklahoma City Metropolitan Area Tree Canopy Assessment. Davey Resource Group. https://tree-canopy-acog.hub.arcgis.com/documents/oklahoma-city-metropolitan-area-tree-canopy-assessment/explore

62. TTF and City of Dallas, 2021: Dallas Urban Forest Master Plan 2021. Texas Trees Foundation and City of Dallas. https://dallascityhall.com/projects/forestry/dch%20documents/city%20of%20dallas%202021%20urban%20forest%20master%20plan.pdf

63. Hopkins, L.P., D.J. January-Bevers, E.K. Caton, and L.A. Campos, 2022: A simple tree planting framework to improve climate, air pollution, health, and urban heat in vulnerable locations using non-traditional partners. *Plants, People, Planet*, **4** (3), 243–257. https://doi.org/10.1002/ppp3.10245

64. Roeland, S., M. Moretti, J.H. Amorim, C. Branquinho, S. Fares, F. Morelli, Ü. Niinemets, E. Paoletti, P. Pinho, G. Sgrigna, V. Stojanovski, A. Tiwary, P. Sicard, and C. Calfapietra, 2019: Towards an integrative approach to evaluate the environmental ecosystem services provided by urban forest. *Journal of Forestry Research*, **30**, 1981–1996. https://doi.org/10.1007/s11676-019-00916-x

65. Lovell, S.T., J. Hayman, H. Hemmelgarn, A.A. Hunter, and J.R. Taylor, 2021: Community orchards for food sovereignty, human health, and climate resilience: Indigenous roots and contemporary applications. *Forests*, **12** (11), 1533. https://doi.org/10.3390/f12111533

66. VanWinkle, T.N. and J. Friedman, 2019: Between drought and disparity: American Indian farmers, resource bureaucracy, and climate vulnerability in the Southern Plains. *Journal of Agriculture, Food Systems, and Community Development*, **9** (B), 53–68. https://doi.org/10.5304/jafscd.2019.09b.022

67. Moda, H.M., W.L. Filho, and A. Minhas, 2019: Impacts of climate change on outdoor workers and their safety: Some research priorities. *International Journal of Environmental Research and Public Health*, **16** (18), 3458. https://doi.org/10.3390/ijerph16183458

68. Benevolenza, M.A. and L. DeRigne, 2019: The impact of climate change and natural disasters on vulnerable populations: A systematic review of literature. *Journal of Human Behavior in the Social Environment*, **29** (2), 266–281. https://doi.org/10.1080/10911359.2018.1527739

69. Newell, R.G. and D. Raimi, 2018: The fiscal impacts of increased U.S. oil and gas development on local governments. *Energy Policy*, **117**, 14–24. https://doi.org/10.1016/j.enpol.2018.02.042

70. Zhang, Y., R. Gautam, S. Pandey, M. Omara, J.D. Maasakkers, P. Sadavarte, D. Lyon, H. Nesser, M.P. Sulprizio, D.J. Varon, R. Zhang, S. Houweling, D. Zavala-Araiza, R.A. Alvarez, A. Lorente, S.P. Hamburg, I. Aben, and D.J. Jacob, 2020: Quantifying methane emissions from the largest oil-producing basin in the United States from space. *Science Advances*, **6** (17), 5120. https://doi.org/10.1126/sciadv.aaz5120

71. ERCOT. 2023: Resource Capacity Trend Charts: Capacity Changes by Fuel Type Charts, April 2023. Electric Reliability Council of Texas. https://www.ercot.com/gridinfo/resource

72. ERCOT. 2023: Monthly Generator Interconnection Status Report (GIS_Report_April_2023). Electric Reliability Council of Texas. https://www.ercot.com/gridinfo/resource

73. BLS, 2023: Quarterly Census of Employment and Wages: Employment and Wages Data Viewer: Third Quarter, 2022: All Industry Levels, One Area. U.S. Bureau of Labor Statistics, accessed May 25, 2023. https://data.bls.gov/cew/apps/data_views/data_views.htm#tab=tables

74. Pollin, R. and B. Callaci, 2019: The economics of just transition: A framework for supporting fossil fuel-dependent workers and communities in the United States. *Labor Studies Journal*, **44** (2), 93–138. https://doi.org/10.1177/0160449x18787051

75. Williams, J.H., R.A. Jones, and M.S. Torn, 2021: Observations on the transition to a net-zero energy system in the United States. *Energy and Climate Change*, **2**, 100050. https://doi.org/10.1016/j.egycc.2021.100050

76. Shoeib, E.A.H., E. Hamin Infield, and H.C. Renski, 2021: Measuring the impacts of wind energy projects on U.S. rural counties' community services and cost of living. *Energy Policy*, **153**, 112279. https://doi.org/10.1016/j.enpol.2021.112279

77. Wimhurst, J.J. and J.S. Greene, 2019: Oklahoma's future wind energy resources and their relationship with the Central Plains low-level jet. *Renewable and Sustainable Energy Reviews*, **115**, 109374. https://doi.org/10.1016/j.rser.2019.109374

78. Bolinger, R.A., V.M. Brown, C.M. Fuhrmann, K.L. Gleason, T.A. Joyner, B.D. Keim, A. Lewis, J.W. Nielsen-Gammon, C.J. Stiles, W. Tollefson, H.E. Attard, and A.M. Bentley, 2022: An assessment of the extremes and impacts of the February 2021 South-Central U.S. Arctic outbreak, and how climate services can help. *Weather and Climate Extremes*, **36**, 100461. https://doi.org/10.1016/j.wace.2022.100461

79. NCEI, 2021: Assessing the U.S. Climate in February 2021. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/news/national-climate-202102

80. NCEI, 2022: Data Tools: Daily Weather Records. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncdc.noaa.gov/cdo-web/datatools/records

81. Glazer, Y.R., D.M. Tremaine, J.L. Banner, M. Cook, R.E. Mace, J. Nielsen-Gammon, E. Grubert, K. Kramer, A.M.K. Stoner, B.M. Wyatt, A. Mayer, T. Beach, R. Correll, and M.E. Webber, 2021: Winter storm Uri: A test of Texas' water infrastructure and water resource resilience to extreme winter weather events. *Journal of Extreme Events*, **08** (04), 2150022. https://doi.org/10.1142/s2345737621500226

82. Hellerstedt, J., 2021: February 2021 Winter Storm-Related Deaths–Texas. Texas Department of State Health Services, 8 pp. https://www.dshs.texas.gov/sites/default/files/news/updates/SMOC_FebWinterStorm_MortalitySurvReport_12-30-21.pdf

83. FERC, 2021: FERC, NERC and Regional Entity Staff Report: The February 2021 Cold Weather Outages in Texas and the South Central United States. Federal Energy Regulatory Commission, North American Electric Reliability Corporation. https://www.naesb.org/pdf4/ferc_nerc_regional_entity_staff_report_feb2021_cold_weather_outages_111621.pdf

84. Ghosh, S., A. Bohra, and S. Dutta, 2021: The Texas freeze of February 2021: Event and winterization analysis using cost and pricing data. In: *2021 IEEE Electrical Power and Energy Conference (EPEC)*. Toronto, ON, 22–31 October 2021. https://doi.org/10.1109/epec52095.2021.9621500

85. Carvallo, J.P., F.C. Hsu, Z. Shah, and J. Taneja, 2021: Frozen Out in Texas: Blackouts and Inequity. The Rockefeller Foundation. https://www.rockefellerfoundation.org/case-study/frozen-out-in-texas-blackouts-and-inequity/

86. Busby, J.W., K. Baker, M.D. Bazilian, A.Q. Gilbert, E. Grubert, V. Rai, J.D. Rhods, S. Shidore, C.A. Smith, and M.E. Webber, 2021: Cascading risks: Understanding the 2021 winter blackout in Texas. *Energy Research & Social Science*, **77**, 102106. https://doi.org/10.1016/j.erss.2021.102106

87. Zhang, X., Y. Fu, Z. Han, J.E. Overland, A. Rinke, H. Tang, T. Vihma, and M. Wang, 2022: Extreme cold events from East Asia to North America in winter 2020/21: Comparisons, causes, and future implications. *Advances in Atmospheric Sciences*, **39** (4), 553–565. https://doi.org/10.1007/s00376-021-1229-1

88. Gao, Y., L.R. Leung, J. Lu, and G. Masato, 2015: Persistent cold air outbreaks over North America in a warming climate. *Environmental Research Letters*, **10** (4), 044001. https://doi.org/10.1088/1748-9326/10/4/044001

89. Relating to Preparing for, Preventing, and Responding to Weather Emergencies and Power Outages; Increasing the Amount of Administrative and Civil Penalties. Texas Senate Bill 3, Texas Legislature, 87th Legislature Regular Session, June 8, 2021. https://capitol.texas.gov/billlookup/history.aspx?legsess=87r&bill=sb3

90. NASS, 2023: News Release: Kansas Rank in U.S. Agriculture. U.S. Department of Agriculture, National Agricultural Statistics Service, 2 pp. https://www.nass.usda.gov/statistics_by_state/kansas/publications/economic_releases/rank/2023/ks-rank23.pdf

91. NASS, 2023: Cattle Inventory–January 1, 2023. U.S. Department of Agriculture, National Agricultural Statistics Service. https://usda.library.cornell.edu/concern/publications/h702q636h

92. NASS, 2019: 2017 Census of Agriculture: United States Summary and State Data. AC-17-A-51. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/agcensus/2017/index.php

93. Settele, J., J. Bishop, and S.G. Potts, 2016: Climate change impacts on pollination. *Nature Plants*, **2** (7), 16092. https://doi.org/10.1038/nplants.2016.92

94. Challinor, A.J., J. Watson, D.B. Lobell, S.M. Howden, D.R. Smith, and N. Chhetri, 2014: A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, **4** (4), 287–291. https://doi.org/10.1038/nclimate2153

95. Allstadt, A.J., S.J. Vavrus, P.J. Heglund, A.M. Pidgeon, W.E. Thogmartin, and V.C. Radeloff, 2015: Spring plant phenology and false springs in the conterminous US during the 21st century. *Environmental Research Letters*, **10** (10), 104008. https://doi.org/10.1088/1748-9326/10/10/104008

96. Chamberlain, C.J., B.I. Cook, I. García de Cortázar-Atauri, and E.M. Wolkovich, 2019: Rethinking false spring risk. *Global Change Biology*, **25** (7), 2209–2220. https://doi.org/10.1111/gcb.14642

97. Tavakol, A., V. Rahmani, and J. Harrington, 2020: Temporal and spatial variations in the frequency of compound hot, dry, and windy events in the central United States. *Scientific Reports*, **10** (1), 15691. https://doi.org/10.1038/s41598-020-72624-0

98. Zhao, H., L. Zhang, M.B. Kirkham, S.M. Welch, J.W. Nielsen-Gammon, G. Bai, J. Luo, D.A. Andresen, C.W. Rice, N. Wan, R.P. Lollato, D. Zheng, P.H. Gowda, and X. Lin, 2022: U.S. winter wheat yield loss attributed to compound hot-dry-windy events. *Nature Communications*, **13** (1), 7233. https://doi.org/10.1038/s41467-022-34947-6

99. Steiner, J.L., D.D. Briske, D.P. Brown, and C.M. Rottler, 2018: Vulnerability of Southern Plains agriculture to climate change. *Climatic Change*, **146** (1), 201–218. https://doi.org/10.1007/s10584-017-1965-5

100. Cho, S.J. and B. McCarl, 2021: Major United States land use as influenced by an altering climate: A spatial econometric approach. *Land*, **10** (5), 546. https://doi.org/10.3390/land10050546

101. Steiner, J.L., D.L. Devlin, S. Perkins, J.P. Aguilar, B. Golden, E.A. Santos, and M. Unruh, 2021: Policy, technology, and management options for water conservation in the Ogallala Aquifer in Kansas, USA. *Water*, **13** (23), 3406. https://doi.org/10.3390/w13233406

102. Drysdale, K.M. and N.P. Hendricks, 2018: Adaptation to an irrigation water restriction imposed through local governance. *Journal of Environmental Economics and Management*, **91**, 150–165. https://doi.org/10.1016/j.jeem.2018.08.002

103. Hegeman, R., 2022: Heat stress blamed for thousands of cattle deaths in Kansas. *The Associated Press*, June 16, 2022. https://apnews.com/article/kansas-cattle-heat-wave-deaths-643f651f1b6118ee6ae4c6833176ce04

104. KDA, 2022: Governor Laura Kelly announces resources, actions to assist cattle producers impacted by heat wave. Kansas Department of Agriculture, Jun 17, 2022. https://agriculture.ks.gov/news-events/news-releases/2022/06/17/governor-laura-kelly-announces-resources-actions-to-assist-cattle-producers-impacted-by-heat-wave

105. Wilmer, H., M.E. Fernández-Giménez, S. Ghajar, P.L. Taylor, C. Souza, and J.D. Derner, 2020: Managing for the middle: Rancher care ethics under uncertainty on western Great Plains rangelands. *Agriculture and Human Values*, **37** (3), 699–718. https://doi.org/10.1007/s10460-019-10003-w

106. Lengnick, L., 2015: *Resilient Agriculture: Cultivating Food Systems for a Changing Climate*. New Society Publishers, 368 pp. https://newsociety.com/books/r/resilient-agriculture-second-edition

107. Smith, A.B. and J.L. Matthews, 2015: Quantifying uncertainty and variable sensitivity within the US billion-dollar weather and climate disaster cost estimates. *Natural Hazards*, **77** (3), 1829–1851. https://doi.org/10.1007/s11069-015-1678-x

108. Marshall, M.I., L.S. Niehm, S.B. Sydnor, and H.L. Schrank, 2015: Predicting small business demise after a natural disaster: An analysis of pre-existing conditions. *Natural Hazards*, **79** (1), 331–354. https://doi.org/10.1007/s11069-015-1845-0

109. Miranda, V.E. and M. Swanstrom, 2020: Surviving disasters: A multi-company case study on disaster recovery plans. *The Journal of Applied Business and Economics*, **22** (6), 87–105. https://doi.org/10.33423/jabe.v22i6.3078

110. Mantripragada, H.C., H. Zhai, and E.S. Rubin, 2019: Boundary Dam or Petra Nova–Which is a better model for CCS energy supply? *International Journal of Greenhouse Gas Control*, **82**, 59–68. https://doi.org/10.1016/j.ijggc.2019.01.004

111. Jones, A.C. and A.J. Lawson, 2021: Carbon Capture and Sequestration (CCS) in the United States. CSR Report R44902. Congressional Research Service. https://sgp.fas.org/crs/misc/R44902.pdf

112. Feder, J., 2021: Geothermal well construction: A step change in oil and gas technologies. *Journal of Petroleum Technology*, **73** (1), 32–35. https://doi.org/10.2118/0121-0032-jpt

113. Clayton, C., 2022: Soil health in central Kansas: Rain still needed, but Kansas soil health tour stresses regenerative AG practices. *DTN Progressive Farmer*, August 3, 2022. https://www.dtnpf.com/agriculture/web/ag/crops/article/2022/08/03/rain-still-needed-kansas-soil-health

114. Gaskill, M., 2021: Paying landowners to store $CO_2$ in soil a promising climate mitigation tool. *Texas Climate News*. https://texasclimatenews.org/2021/04/15/paying-landowners-to-store-co2-in-soil-a-promising-climate-mitigation-tool/

115. Raw, K., E. Sherry, and K. Rowe, 2022: Sport for social cohesion: Exploring aims and complexities. *Sport Management Review*, **25** (3), 454–475. https://doi.org/10.1080/14413523.2021.1949869

116. Finch, B., 2022: Disaster relief efforts of Houston sport organizations. *Sport, Business and Management: An International Journal*, **12** (3), 253–268. https://doi.org/10.1108/sbm-11-2020-0120

117. Hemmer, L. and D.S. Elliff, 2019: Leaders in action: The experiences of seven Texas superintendents before, during, and after Hurricane Harvey. *Educational Management Administration & Leadership*, **48** (6), 964–985. https://doi.org/10.1177/1741143219873073

118. Orr, M., Y. Inoue, R. Seymour, and G. Dingle, 2022: Impacts of climate change on organized sport: A scoping review. *WIREs Climate Change*, **13** (3), 760. https://doi.org/10.1002/wcc.760

119. Rundell, K.W., 2012: Effect of air pollution on athlete health and performance. *British Journal of Sports Medicine*, **46** (6), 407–412. https://doi.org/10.1136/bjsports-2011-090823

120. Bernard, P., G. Chevance, C. Kingsbury, A. Baillot, A.J. Romain, V. Molinier, T. Gadais, and K.N. Dancause, 2021: Climate change, physical activity and sport: A systematic review. *Sports Medicine*, **51**, 1041–1059. https://doi.org/10.1007/s40279-021-01439-4

121. Ebi, K.L., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, and O. Jay, 2021: Hot weather and heat extremes: Health risks. *The Lancet*, **398** (10301), 698–708. https://doi.org/10.1016/s0140-6736(21)01208-3

122. Brocherie, F., O. Girard, and G.P. Millet, 2015: Emerging environmental and weather challenges in outdoor sports. *Climate*, **3** (3), 492–521. https://doi.org/10.3390/cli3030492

123. Cunningham, G.B., P. Wicker, and B.P. McCullough, 2020: Pollution, health, and the moderating role of physical activity opportunities. *International Journal of Environmental Research and Public Health*, **17** (17). https://doi.org/10.3390/ijerph17176272

124. Taylor, W.C., M.F. Floyd, M.C. Whitt-Glover, and J. Brooks, 2007: Environmental justice: A framework for collaboration between the public health and parks and recreation fields to study disparities in physical activity. *Journal of Physical Activity and Health*, **4** (s1), S50–S63. https://doi.org/10.1123/jpah.4.s1.s50

125. Cantu, A., M.A. Graham, A.V. Millard, I. Flores, M.K. Mugleston, I.Y. Reyes, and E.S. Carbajal, 2016: Environmental justice and community-based research in Texas borderland colonias. *Public Health Nursing*, **33** (1), 65–72. https://doi.org/10.1111/phn.12187

126. Lee-Chiong, T.L. and J.T. Stitt, 1995: Heatstroke and other heat-related illnesses: The maladies of summer. *Postgraduate Medicine*, **98** (1), 26–36. https://doi.org/10.1080/00325481.1995.11946015

127. Yeargin, S.W., E. Cahoon, Y. Hosokawa, J.M. Mensch, T.P. Dompier, and Z.Y. Kerr, 2017: Environmental conditions and seasonal variables in American youth football leagues. *Clinical Pediatrics*, **56** (13), 1209–1218. https://doi.org/10.1177/0009922816684603

128. Grundstein, A., E. Cooper, M. Ferrara, and J.A. Knox, 2014: The geography of extreme heat hazards for American football players. *Applied Geography*, **46**, 53–60. https://doi.org/10.1016/j.apgeog.2013.10.007

129. Bergeron, M.F., 2014: Heat stress and thermal strain challenges in running. *Journal of Orthopaedic & Sports Physical Therapy*, **44** (10), 831–838. https://doi.org/10.2519/jospt.2014.5500

130. Bergeron, M.F., C. DiLaura Devore, and S.G. Rice, 2011: Climatic heat stress and exercising children and adolescents. *Pediatrics*, **128** (3), 747. https://doi.org/10.1542/peds.2011-1664

131. Cheng, W., J.O. Spengler, and R.D. Brown, 2020: A comprehensive model for estimating heat vulnerability of young athletes. *International Journal of Environmental Research and Public Health*, **17** (17), 6156. https://doi.org/10.3390/ijerph17176156

132. Vanos, J.K., A.J. Herdt, and M.R. Lochbaum, 2017: Effects of physical activity and shade on the heat balance and thermal perceptions of children in a playground microclimate. *Building and Environment*, **126**, 119–131. https://doi.org/10.1016/j.buildenv.2017.09.026

133. Vanos, J.K., 2015: Children's health and vulnerability in outdoor microclimates: A comprehensive review. *Environment International*, **76**, 1–15. https://doi.org/10.1016/j.envint.2014.11.016

134. Rigolon, A., 2016: A complex landscape of inequity in access to urban parks: A literature review. *Landscape and Urban Planning*, **153**, 160–169. https://doi.org/10.1016/j.landurbplan.2016.05.017

135. Kellison, T. and M. Orr, 2021: Climate vulnerability as a catalyst for early stadium replacement. *International Journal of Sports Marketing and Sponsorship*, **22** (1), 126–141. https://doi.org/10.1108/ijsms-04-2020-0076

136. Murfree, J.R. and A.M. Moorman, 2021: An examination and analysis of Division I football game contracts: Legal implications of game cancellations due to hurricanes. *Journal of Legal Aspects of Sport*, **31** (1), 123–146. https://doi.org/10.18060/24922

137. Orr, M. and Y. Inoue, 2019: Sport versus climate: Introducing the climate vulnerability of sport organizations framework. *Sport Management Review*, **22** (4), 452–463. https://doi.org/10.1016/j.smr.2018.09.007

138. Yasarer, L.M.W. and B.S.M. Sturm, 2016: Potential impacts of climate change on reservoir services and management approaches. *Lake and Reservoir Management*, **32** (1), 13–26. https://doi.org/10.1080/10402381.2015.1107665

139. Lewis, J.M., D.J. Williams, S.J. Harris, and A.R. Trevisan, 2020: Characterization of Peak Streamflow and Stages at Selected Streamgages in Eastern and Northeastern Oklahoma from the May to June 2019 Flood Event—With an Emphasis on Flood Peaks Downstream from Dams and on Tributaries to the Arkansas River. USGS Open-File Report 2020-1090. U.S. Geological Survey, 18 pp. https://doi.org/10.3133/ofr20201090

140. Loveless, B., 2020: KDWPT Update to the Senate Committee on Agriculture and Natural Resources. Kansas Department of Wildlife, Parks, and Tourism, Topeka, KS, 2 pp. http://kslegislature.org/li/b2019_20/committees/ctte_s_agriculture_and_natural_resources_1/documents/testimony/20200115_01.pdf

141. Thomas, D.S.K., O.V. Wilhelmi, T.N. Finnessey, and V. Deheza, 2013: A comprehensive framework for tourism and recreation drought vulnerability reduction. *Environmental Research Letters*, **8** (4), 044004. https://doi.org/10.1088/1748-9326/8/4/044004

142. Osland, M.J., A.R. Hughes, A.R. Armitage, S.B. Scyphers, J. Cebrian, S.H. Swinea, C.C. Shepard, M.S. Allen, L.C. Feher, J.A. Nelson, C.L. O'Brien, Colt R. Sanspree, D.L. Smee, C.M. Snyder, A.P. Stetter, Philip W. Stevens, K.M. Swanson, L.H. Williams, Janell M. Brush, J. Marchionno, and R. Bardou, 2022: The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: Current understanding, knowledge gaps, and emerging research needs. *Global Change Biology*, **28** (10), 3163–3187. https://doi.org/10.1111/gcb.16111

143. Dunning, K.H., 2021: Adaptive governance of recreational ecosystem services following a major hurricane. *Ecosystem Services*, **50**, 101324. https://doi.org/10.1016/j.ecoser.2021.101324

144. Dunning, K.H., 2020: Building resilience to natural hazards through coastal governance: A case study of Hurricane Harvey recovery in Gulf of Mexico communities. *Ecological Economics*, **176**, 106759. https://doi.org/10.1016/j.ecolecon.2020.106759

145. Wallace, D.J. and J.B. Anderson, 2013: Unprecedented erosion of the upper Texas coast: Response to accelerated sea-level rise and hurricane impacts. *GSA Bulletin*, **125** (5-6), 728–740. https://doi.org/10.1130/b30725.1

146. Armitage, A.R., W.E. Highfield, S.D. Brody, and P. Louchouarn, 2015: The contribution of mangrove expansion to salt marsh loss on the Texas Gulf Coast. *PLoS ONE*, **10** (5), 0125404. https://doi.org/10.1371/journal.pone.0125404

147. Tolan, J.M., 2007: El Niño-Southern Oscillation impacts translated to the watershed scale: Estuarine salinity patterns along the Texas Gulf Coast, 1982 to 2004. *Estuarine, Coastal and Shelf Science*, **72** (1–2), 247–260. https://doi.org/10.1016/j.ecss.2006.10.018

148. Pathak, A. and A. Fuller, 2021: Vulnerability and Adaptation to Climate Change: An Assessment for the Texas Mid-Coast. National Wildlife Federation, Austin, TX. https://texaslivingwaters.org/wp-content/uploads/2021/05/Mid-Coast-Assessment.pdf

149. Pawluk, M., M. Fujiwara, and F. Martinez-Andrade, 2021: Climate effects on fish diversity in the subtropical bays of Texas. *Estuarine, Coastal and Shelf Science*, **249**, 107121. https://doi.org/10.1016/j.ecss.2020.107121

150. Fujiwara, M., F. Martinez-Andrade, R.J.D. Wells, M. Fisher, M. Pawluk, and M.C. Livernois, 2019: Climate-related factors cause changes in the diversity of fish and invertebrates in subtropical coast of the Gulf of Mexico. *Communications Biology*, **2** (1), 1–9. https://doi.org/10.1038/s42003-019-0650-9

151. BEA, 2021: Outdoor Recreation Satellite Account (ORSA): 2020—Texas. U.S. Department of Commerce, Bureau of Economic Analysis, 2 pp. https://apps.bea.gov/data/special-topics/orsa/summary-sheets/orsa%20-%20texas.pdf

152. Cady, S.M., T.J. O'Connell, S.R. Loss, N.E. Jaffe, and C.A. Davis, 2019: Species-specific and temporal scale-dependent responses of birds to drought. *Global Change Biology*, **25** (8), 2691–2702. https://doi.org/10.1111/gcb.14668

153. Porro, C.M., M.J. Desmond, J.A. Savidge, F. Abadi, K.K. Cruz-McDonnell, J.L. Davis, R.L. Griebel, R.T. Ekstein, and N.H. Rodríguez, 2020: Burrowing Owl (*Athene cunicularia*) nest phenology influenced by drought on nonbreeding grounds. *The Auk*, **137** (2), ukaa008. https://doi.org/10.1093/auk/ukaa008

154. Chen, I.-C., J.K. Hill, R. Ohlemüller, D.B. Roy, and C.D. Thomas, 2011: Rapid range shifts of species associated with high levels of climate warming. *Science*, **333** (6045), 1024–1026. https://doi.org/10.1126/science.1206432

155. Sheridan, J.A. and D. Bickford, 2011: Shrinking body size as an ecological response to climate change. *Nature Climate Change*, **1** (8), 401–406. https://doi.org/10.1038/nclimate1259

156. Knight, S., 2021: A changing world: Ducks are still coming, how they are hunted is evolving. *Tyler Morning Telegraph*, November 4, 2021. https://tylerpaper.com/opinion/columnists/a-changing-world-ducks-are-still-coming-how-they-are-hunted-is-evolving/article_5f1ec2d4-3db0-11ec-a4d0-bb141b0f764d.html

157. Brody, S., R. Blessing, A. Sebastian, and P. Bedient, 2014: Examining the impact of land use/land cover characteristics on flood losses. *Journal of Environmental Planning and Management*, **57** (8), 1252–1265. https://doi.org/10.1080/09640568.2013.802228

158. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

159. Marino, E., 2018: Adaptation privilege and voluntary buyouts: Perspectives on ethnocentrism in sea level rise relocation and retreat policies in the US. *Global Environmental Change*, **49**, 10–13. https://doi.org/10.1016/j.gloenvcha.2018.01.002

160. Martinich, J., J. Neumann, L. Ludwig, and L. Jantarasami, 2013: Risks of sea level rise to disadvantaged communities in the United States. *Mitigation and Adaptation Strategies for Global Change*, **18** (2), 169–185. https://doi.org/10.1007/s11027-011-9356-0

161. Arora, S. and D. Glover, 2017: Power in Practice: Insights from Technography and Actor-Network Theory for Agricultural Sustainability. STEPS Working Paper 100. STEPS Centre, Brighton, UK. https://steps-centre.org/publication/power-practice-insights-technography-actor-network-theory-agricultural-sustainability/

162. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

163. Kapucu, N., C.V. Hawkins, and F.I. Rivera, 2013: Disaster preparedness and resilience for rural communities. *Risk, Hazards & Crisis in Public Policy*, **4** (4), 215–233. https://doi.org/10.1002/rhc3.12043

164. McDonald, R.I., T. Biswas, C. Sachar, I. Housman, T.M. Boucher, D. Balk, D. Nowak, E. Spotswood, C.K. Stanley, and S. Leyk, 2021: The tree cover and temperature disparity in US urbanized areas: Quantifying the association with income across 5,723 communities. *PLoS ONE*, **16** (4), e0249715. https://doi.org/10.1371/journal.pone.0249715

165. Zhou, W., G. Huang, S.T.A. Pickett, J. Wang, M.L. Cadenasso, T. McPhearson, J.M. Grove, and J. Wang, 2021: Urban tree canopy has greater cooling effects in socially vulnerable communities in the US. *One Earth*, **4** (12), 1764–1775. https://doi.org/10.1016/j.oneear.2021.11.010

166. Goodling, E., 2020: Intersecting hazards, intersectional identities: A baseline Critical Environmental Justice analysis of US homelessness. *Environment and Planning E: Nature and Space*, **3** (3), 833–856. https://doi.org/10.1177/2514848619892433

167. Pellow, D.N., 2021: Struggles for environmental justice in US prisons and jails. *Antipode*, **53** (1), 56–73. https://doi.org/10.1111/anti.12569

168. Skarha, J., M. Peterson, J.D. Rich, and D. Dosa, 2020: An overlooked crisis: Extreme temperature exposures in incarceration settings. *American Journal of Public Health*, **110** (S1), S41–S42. https://doi.org/10.2105/ajph.2019.305453

169. Chakraborty, J., T.W. Collins, and S.E. Grineski, 2019: Exploring the environmental justice implications of Hurricane Harvey flooding in Greater Houston, Texas. *American Journal of Public Health*, **109**, 244–250. https://doi.org/10.2105/ajph.2018.304846

170. Deria, A., P. Ghannad, and Y.-C. Lee, 2020: Evaluating implications of flood vulnerability factors with respect to income levels for building long-term disaster resilience of low-income communities. *International Journal of Disaster Risk Reduction*, **48**, 101608. https://doi.org/10.1016/j.ijdrr.2020.101608

171. Hendricks, M.D. and S. Van Zandt, 2021: Unequal protection revisited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. *Environmental Justice*, **14** (2), 87–97. https://doi.org/10.1089/env.2020.0054

172. Johnston, J. and L. Cushing, 2020: Chemical exposures, health, and environmental justice in communities living on the fenceline of industry. *Current Environmental Health Reports*, **7**, 48–57. https://doi.org/10.1007/s40572-020-00263-8

173. Madrigano, J., J.C. Osorio, E. Bautista, R. Chavez, C.F. Chaisson, E. Meza, R.A. Shih, and R. Chari, 2018: Fugitive chemicals and environmental justice: A model for environmental monitoring following climate-related disasters. *Environmental Justice*, **11** (3), 95–100. https://doi.org/10.1089/env.2017.0044

174. Flores, A.B., A. Castor, S.E. Grineski, T.W. Collins, and C. Mullen, 2021: Petrochemical releases disproportionately affected socially vulnerable populations along the Texas Gulf Coast after Hurricane Harvey. *Population and Environment*, **42** (3), 279–301. https://doi.org/10.1007/s11111-020-00362-6

175. Summers, K., A. Lamper, and K. Buck, 2021: National hazards vulnerability and the remediation, restoration and revitalization of contaminated sites—1. Superfund. *Environmental Management*, **67** (6), 1029–1042. https://doi.org/10.1007/s00267-021-01459-w

176. Burleson, D.W., H.S. Rifai, J.K. Proft, C.N. Dawson, and P.B. Bedient, 2015: Vulnerability of an industrial corridor in Texas to storm surge. *Natural Hazards*, **77** (2), 1183–1203. https://doi.org/10.1007/s11069-015-1652-7

177. de Bruijn, K., J. Buurman, M. Mens, R. Dahm, and F. Klijn, 2017: Resilience in practice: Five principles to enable societies to cope with extreme weather events. *Environmental Science & Policy*, **70**, 21–30. https://doi.org/10.1016/j.envsci.2017.02.001

178. Weden, M.M., V. Parks, A.M. Parker, L. Drakeford, and R. Ramchand, 2021: Health disparities in the U.S. Gulf Coast: The interplay of environmental disaster, material loss, and residential segregation. *Environmental Justice*, **14** (2), 110–123. https://doi.org/10.1089/env.2020.0049

179. Hamideh, S. and J. Rongerude, 2018: Social vulnerability and participation in disaster recovery decisions: Public housing in Galveston after Hurricane Ike. *Natural Hazards*, **93**, 1629–1648. https://doi.org/10.1007/s11069-018-3371-3

180. Cordova, S.J., 2022: Federal Indian policy and the fulfillment of the trust responsibility for disaster management in Indian country. In: *Justice, Equity, and Emergency Management*. Jerolleman, A. and W.L. Waugh, Eds. Emerald Publishing Limited, 89–106. https://doi.org/10.1108/s2040-726220220000025005

181. Farrell, J., P.B. Burow, K. McConnell, J. Bayham, K. Whyte, and G. Koss, 2021: Effects of land dispossession and forced migration on Indigenous peoples in North America. *Science*, **374** (6567), 4943. https://doi.org/10.1126/science.abe4943

182. Schramm, P.J., A.L.A. Janabi, L.W. Campbell, J.L. Donatuto, and S.C. Gaughen, 2020: How Indigenous communities are adapting to climate change: Insights from the Climate-Ready Tribes Initiative. *Health Affairs*, **39** (12), 2153–2159. https://doi.org/10.1377/hlthaff.2020.00997

183. Schlosberg, D. and L.B. Collins, 2014: From environmental to climate justice: Climate change and the discourse of environmental justice. *WIREs Climate Change*, **5** (3), 359–374. https://doi.org/10.1002/wcc.275

184. City of El Paso, 2016: Resilient El Paso. City of El Paso, 114 pp. https://www.elpasotexas.gov/assets/Documents/CoEP/Community-Development/Forms-and-Notices/2023-NOFA/City-of-El-Paso-Resilience-Strategy.pdf

185. Norton-Smith, K., K. Lynn, K. Chief, K. Cozzetto, J. Donatuto, M.H. Redsteer, L.E. Kruger, J. Maldonado, C. Viles, and K.P. Whyte, 2016: Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences. Gen. Tech. Rep. PNW-GTR-944. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 136 pp. https://www.fs.usda.gov/treesearch/pubs/53156

186. Bartle, J.R. and D. Leuenberger, 2006: The idea of sustainable development in public administration. *Public Works Management & Policy*, **10** (3), 191–194. https://doi.org/10.1177/1087724X06287507

187. Giner, M.-E. and M. Pavon, 2021: A retrospective analysis of program outcomes and lessons learned on implementing first-time wastewater infrastructure in underserved communities in Texas from 1995 through 2017. *Environmental Challenges*, **5**, 100342. https://doi.org/10.1016/j.envc.2021.100342

188. Guerra Uribe, M., K.M. Faust, and J. Charnitski, 2019: Policy driven water sector and energy dependencies in Texas border colonias. *Sustainable Cities and Society*, **48**, 101568. https://doi.org/10.1016/j.scs.2019.101568

189. Brikowski, T.H., 2008: Doomed reservoirs in Kansas, USA? Climate change and groundwater mining on the Great Plains lead to unsustainable surface water storage. *Journal of Hydrology*, **354** (1), 90–101. https://doi.org/10.1016/j.jhydrol.2008.02.020

190. Nielsen-Gammon, J.W., J.L. Banner, B.I. Cook, D.M. Tremaine, C.I. Wong, R.E. Mace, H. Gao, Z.-L. Yang, M.F. Gonzalez, R. Hoffpauir, T. Gooch, and K. Kloesel, 2020: Unprecedented drought challenges for Texas water resources in a changing climate: What do researchers and stakeholders need to know? *Earth's Future*, **8** (8), e2020EF001552. https://doi.org/10.1029/2020ef001552

191. Dellapenna, T.M., C. Hoelscher, L. Hill, M.E. Al Mukaimi, and A. Knap, 2020: How tropical cyclone flooding caused erosion and dispersal of mercury-contaminated sediment in an urban estuary: The impact of Hurricane Harvey on Buffalo Bayou and the San Jacinto Estuary, Galveston Bay, USA. *Science of The Total Environment*, **748**, 141226. https://doi.org/10.1016/j.scitotenv.2020.141226

192. Lee, C. and G. Foster, 2013: Assessing the potential of reservoir outflow management to reduce sedimentation using continuous turbidity monitoring and reservoir modelling. *Hydrological Processes*, **27** (10), 1426–1439. https://doi.org/10.1002/hyp.9284

193. Mulki, S., C. Rubinstein, and J. Saletta, 2018: Texas' water quality challenge and the need for better communication in an era of increasing water quality contamination events. *Texas Water Journal*, **9** (1), 108–119. https://doi.org/10.21423/twj.v9i1.7059

194. Anderson, F. and N. Al-Thani, 2016: Effect of sea level rise and groundwater withdrawal on seawater intrusion in the Gulf Coast aquifer: Implications for agriculture. *Journal of Geoscience and Environment Protection*, **4** (4), 116–124. https://doi.org/10.4236/gep.2016.44015

195. Chowdhury, A.H., B.R. Scanlon, R.C. Reedy, and S. Young, 2018: Fingerprinting groundwater salinity sources in the Gulf Coast Aquifer System, USA. *Hydrogeology Journal*, **26** (1), 197–213. https://doi.org/10.1007/s10040-017-1619-8

196. Liu, Y., J. Li, J. Fasullo, and D.L. Galloway, 2020: Land subsidence contributions to relative sea level rise at tide gauge Galveston Pier 21, Texas. *Scientific Reports*, **10** (1), 17905. https://doi.org/10.1038/s41598-020-74696-4

197. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

198. ASCE, 2021: A Comprehensive Assessment of America's Infrastructure: 2021 Report Card for America's Infrastructure. American Society of Civil Engineers. https://infrastructurereportcard.org/

199. Oklahoma DOT, 2020: Oklahoma Long Range Transportation Plan: 2020–2045. Oklahoma Department of Transportation. https://www.oklongrangeplan.org/

200. Texas DOT, 2020: Texas Transportation Plan 2050. Texas Department of Transportation. https://ftp.dot.state.tx.us/pub/txdot/tpp/2050/ttp-2050.pdf

201. Kansas DOT, 2021: Kansas Long Range Transportation Plan: 2020–2045. Kansas Department of Transportation. https://www.ksdot.org/assets/wwwksdotorg/bureaus/burtransplan/documents/kdot_lrtp.pdf

202. Zottarelli, L.K., H.O. Sharif, X. Xu, and T.S. Sunil, 2021: Effects of social vulnerability and heat index on emergency medical service incidents in San Antonio, Texas, in 2018. *Journal of Epidemiology and Community Health*, **75** (3), 271–276. https://doi.org/10.1136/jech-2019-213256

203. Lindley, T., D. Speheger, M. Day, G. Murdoch, B. Smith, N. Nauslar, and D. Daily, 2019: Megafires on the Southern Great Plains. *Journal of Operational Meteorology*, **7** (12), 164. https://doi.org/10.15191/nwajom.2019.0712

204. Donovan, V.M., C.L. Wonkka, D.A. Wedin, and D. Twidwell, 2020: Land-use type as a driver of large wildfire occurrence in the U.S. Great Plains. *Remote Sensing*, **12** (11), 1869. https://doi.org/10.3390/rs12111869

205. Busch, K.C., J.A. Henderson, and K.T. Stevenson, 2019: Broadening epistemologies and methodologies in climate change education research. *Environmental Education Research*, **25** (6), 955–971. https://doi.org/10.1080/13504622.2018.1514588

206. Colston, N.M. and T.A. Ivey, 2015: (Un)doing the Next Generation Science Standards: Climate change education actor-networks in Oklahoma. *Journal of Education Policy*, **30** (6), 773–795. https://doi.org/10.1080/02680939.2015.1011711

207. KSDE, 2013: Kansas Science Standards—The Kansas College and Career Ready Standards for Science (KCCRSS): Disciplinary Core Ideas Arrangement. Kansas State Department of Education, Topeka, KS. https://community.ksde.org/Default.aspx?tabid=5785

208. TEA, 2022: Texas Essential Knowledge and Skills for Science. Texas Education Agency. https://tea.texas.gov/about-tea/laws-and-rules/texas-administrative-code/19-tac-chapter-112

209. Foss, A.W. and Y. Ko, 2019: Barriers and opportunities for climate change education: The case of Dallas-Fort Worth in Texas. *The Journal of Environmental Education*, **50** (3), 145–159. https://doi.org/10.1080/00958964.2019.1604479

210. Cook, J., N. Oreskes, P.T. Doran, W.R.L. Anderegg, B. Verheggen, E.W. Maibach, J.S. Carlton, S. Lewandowsky, A.G. Skuce, S.A. Green, D. Nuccitelli, P. Jacobs, M. Richardson, B. Winkler, R. Painting, and K. Rice, 2016: Consensus on consensus: A synthesis of consensus estimates on human-caused global warming. *Environmental Research Letters*, **11** (4), 048002. https://doi.org/10.1088/1748-9326/11/4/048002

211. Martin, E., R. McPherson, E. Kuster, and A. Bamzai-Dodson, 2020: Managing for a changing climate: A blended interdisciplinary climate course. *Bulletin of the American Meteorological Society*, **101** (12), E2138–E2148. https://doi.org/10.1175/bams-d-19-0242.1

212. Monroe, M.C., R.R. Plate, A. Oxarart, A. Bowers, and W.A. Chaves, 2019: Identifying effective climate change education strategies: A systematic review of the research. *Environmental Education Research*, **25** (6), 791–812. https://doi.org/10.1080/13504622.2017.1360842

213. Solis, M., W. Davies, and A. Randall, 2022: Climate justice pedagogies in green building curriculum. *Curriculum Inquiry*, **52** (2), 235–249. https://doi.org/10.1080/03626784.2022.2041981

214. Lake, P., 2021: Texas reimagines the fight against floods. *Texas Water Journal*, **12** (1), 58–67. https://doi.org/10.21423/twj.v12i1.7133

215. McPherson, R.A., C.A. Fiebrich, K.C. Crawford, J.R. Kilby, D.L. Grimsley, J.E. Martinez, J.B. Basara, B.G. Illston, D.A. Morris, K.A. Kloesel, A.D. Melvin, H. Shrivastava, J.M. Wolfinbarger, J.P. Bostic, D.B. Demko, R.L. Elliott, S.J. Stadler, J.D. Carlson, and A.J. Sutherland, 2007: Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet. *Journal of Atmospheric and Oceanic Technology*, **24** (3), 301–321. https://doi.org/10.1175/jtech1976.1

216. Patrignani, A., M. Knapp, C. Redmond, and E. Santos, 2020: Technical overview of the Kansas Mesonet. *Journal of Atmospheric and Oceanic Technology*, **37** (12), 2167–2183. https://doi.org/10.1175/jtech-d-19-0214.1

217. Schroeder, J.L., W.S. Burgett, K.B. Haynie, I. Sonmez, G.D. Skwira, A.L. Doggett, and J.W. Lipe, 2005: The West Texas Mesonet: A technical overview. *Journal of Atmospheric and Oceanic Technology*, **22** (2), 211–222. https://doi.org/10.1175/jtech-1690.1

218. Adeel, Z., A.M. Alarcón, L. Bakkensen, E. Franco, G.M. Garfin, R.A. McPherson, K. Méndez, M.B. Roudaut, H. Saffari, and X. Wen, 2020: Developing a comprehensive methodology for evaluating economic impacts of floods in Canada, Mexico and the United States. *International Journal of Disaster Risk Reduction*, **50**, 101861. https://doi.org/10.1016/j.ijdrr.2020.101861

219. Jenkins-Smith, H., J. Ripberger, C. Silva, N. Carlson, K. Gupta, M. Henderson, and A. Goodin, 2017: The Oklahoma meso-scale integrated socio-geographic network: A technical overview. *Journal of Atmospheric and Oceanic Technology*, **34** (11), 2431–2441. https://doi.org/10.1175/jtech-d-17-0088.1

220. Kindsvater, H.K., N.K. Dulvy, C. Horswill, M.-J. Juan-Jordá, M. Mangel, and J. Matthiopoulos, 2018: Overcoming the data crisis in biodiversity conservation. *Trends in Ecology & Evolution*, **33** (9), 676–688. https://doi.org/10.1016/j.tree.2018.06.004

221. Marston, L.T., A.M. Abdallah, K.J. Bagstad, K. Dickson, P. Glynn, S.G. Larsen, F.S. Melton, K. Onda, J.A. Painter, J. Prairie, B.L. Ruddell, R.R. Rushforth, G.B. Senay, and K. Shaffer, 2022: Water-use data in the United States: Challenges and future directions. *JAWRA Journal of the American Water Resources Association*, **58** (4), 485–495. https://doi.org/10.1111/1752-1688.13004

222. City of Oklahoma City, 2020: ADAPTOKC: Adapting for a Healthy Future. City of Oklahoma, City Planning Department, Oklahoma City, OK. https://www.okc.gov/home/showpublisheddocument/18882/637299972915330000

223. City of Austin, 2018: Climate Resilience Action Plan for City Assets and Operations. City of Austin, Office of Sustainability, Austin, TX. https://www.austintexas.gov/sites/default/files/files/Sustainability/Climate_Resilience_Action_Plan.compressed.pdf

224. City of San Antonio, 2019: SA Climate Ready: A Pathway for Climate Action and Adaptation. City of San Antonio, San Antonio, TX, 92 pp. https://www.sanantonio.gov/portals/0/files/sustainability/saclimateready/sacrreportoctober2019.pdf

225. City of Dallas, 2020: Dallas Comprehensive Environmental and Climate Action Plan. City of Dallas, Office of Environmental Quality and Sustainability. https://www.dallasclimateaction.com/_files/ugd/349b65_e4f9a262cebf41258fd4343d9af0504f.pdf

226. FEMA, 2022: City of Tulsa rises to the top as a leader in risk reduction. *FEMA.gov*. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/blog/city-tulsa-rises-top-leader-risk-reduction

227. Kansas Water Office, 2022: The 2022 Kansas Water Plan. Kansas Water Office, Topeka, KS. https://kwo.ks.gov/docs/default-source/water-vision-water-plan/water-plan/finaldraft_kansaswaterplan_080522.pdf?sfvrsn=eefb8114_2

228. Cox, T., M. McCluskey, and K. Arthur, 2012: Incorporating Climate Change into Water Supply Planning and Yield Studies: A Demonstration and Comparison of Practical Methods. State of Oklahoma, Oklahoma Water Resources Board. https://www.owrb.ok.gov/ocwp/pdf/2012update/ocwp_watersmartclimatechangereport.pdf

229. TWDB, 2021: 2022 State Water Plan: Water for Texas. Texas Water Development Board. http://www.twdb.texas.gov/waterplanning/swp/2022/

230. Diringer, S., M. Shimabuku, H. Cooley, M. Gorchels, J. Walker, and S. Leurig, 2020: Scaling Green Stormwater Infrastructure Through Multiple Benefits in Austin, Texas: Distributed Rainwater Capture on Residential Properties in the Waller Creek Watershed. Pacific Institute, Oakland, CA. https://pacinst.org/publication/multiple-benefits-in-austin-texas/

231. Wade, M., R. Peppler, and A. Person, 2021: Community education and perceptions of water reuse: A case study in Norman, Oklahoma. *Journal of Environmental Studies and Sciences*, **11** (2), 266–273. https://doi.org/10.1007/s13412-021-00667-4

232. Beezhold, M.T. and D.W. Baker, 2006: Rain to recreation: Making the case for a stormwater capital recovery fee. *Proceedings of the Water Environment Federation*, **2006** (9), 3814–3825. https://mostcenter.umd.edu/rain-recreation-making-case-stormwater-capital-recovery-fee

233. Jayakaran, A.D., E. Rhodes, and J. Vogel, 2021: Stormwater management at the lot level: Engaging homeowners and business owners to adopt green stormwater infrastructure. In: *Oxford Research Encyclopedia of Environmental Science*. Oxford University Press. https://doi.org/10.1093/acrefore/9780199389414.013.653

234. Smith, D.J. and D. Sutter, 2013: Response and recovery after the Joplin tornado: Lessons applied and lessons learned. *The Independent Review*, **18** (2), 165–188. https://www.independent.org/publications/tir/article.asp?id=953

235. Westfall, N., E. Nelson, and B. Moorhead, 2019: Time and Treasure: Faith-Based Investment in Hurricane Harvey Response. Texas Interfaith Center for Public Policy, Austin, TX, 10 pp. https://texasimpact.org/time-treasure/

236. Hayhoe, K., 2021: *Saving Us: A Climate Scientist's Case for Hope and Healing in a Divided World*. Atria/One Signal Publishers, 320 pp. https://www.simonandschuster.com/books/saving-us/katharine-hayhoe/9781982143831

237. Gottlieb, R.S., ed, 2006: *The Oxford Handbook of Religion and Ecology*. Oxford University Press, USA. https://doi.org/10.1093/oxfordhb/9780195178722.001.0001

238. Haluza-DeLay, R., 2014: Religion and climate change: Varieties in viewpoints and practices. *WIREs Climate Change*, **5** (2), 261–279. https://doi.org/10.1002/wcc.268

239. White, S.S., 2010: Out of the rubble and towards a sustainable future: The "greening" of Greensburg, Kansas. *Sustainability*, **2** (7), 2302–2319. https://doi.org/10.3390/su2072302

240. BNIM Architects, 2008: Greensburg Sustainable Comprehensive Plan. BNIM Architects, Greensburg, KS. https://icma.org/documents/greensburg-sustainable-comprehensive-plan

241. Brundiers, K. and H.C. Eakin, 2018: Leveraging post-disaster windows of opportunities for change towards sustainability: A framework. *Sustainability*, **10** (5), 1390. https://doi.org/10.3390/su10051390

242. Paul, B.K. and D. Che, 2011: Opportunities and challenges in rebuilding tornado-impacted Greensburg, Kansas as "stronger, better, and greener". *GeoJournal*, **76** (1), 93–108. https://doi.org/10.1007/s10708-010-9404-4

243. Sparks, L.H. and S.S. White, 2013: Going green? The impacts of sustainability planning in Greensburg, Kansas, USA. *International Journal of Sustainable Development and Planning*, **8** (3), 288–304. https://doi.org/10.2495/sdp-v8-n3-288-304

244. IPCC, 2018: Summary for policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–24. https://doi.org/10.1017/9781009157940.001

245. EIA, 2022: Introduction and Key Concepts: State Energy-Related Carbon Dioxide Emissions Tables. U.S. Department of Energy, U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/environment/emissions/state/

246. Global Change Research Act of 1990. 101st Congress, Pub. L. No. 101-606, 104 Stat. 3096–3104, November 16, 1990. https://www.congress.gov/bill/101st-congress/senate-bill/169/text

247. TPWD, 2022: Private Landowners and Listed Species. Texas Parks and Wildlife Department. https://tpwd.texas.gov/huntwild/wild/wildlife_diversity/nongame/listed-species/landowner-tools.phtml

248. Miller, N., J. Tack, and J. Bergtold, 2021: The impacts of warming temperatures on US sorghum yields and the potential for adaptation. *American Journal of Agricultural Economics*, **103** (5), 1742–1758. https://doi.org/10.1111/ajae.12223

249. Rojas-Downing, M.M., A.P. Nejadhashemi, T. Harrigan, and S.A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145–163. https://doi.org/10.1016/j.crm.2017.02.001

250. Doss-Gollin, J., D.J. Farnham, U. Lall, and V. Modi, 2021: How unprecedented was the February 2021 Texas cold snap? *Environmental Research Letters*, **16** (6), 064056. https://doi.org/10.1088/1748-9326/ac0278

251. Heynen, N., H.A. Perkins, and P. Roy, 2006: The political ecology of uneven urban green space: The impact of political economy on race and ethnicity in producing environmental inequality in Milwaukee. *Urban Affairs Review*, **42** (1), 3–25. https://doi.org/10.1177/1078087406290729

252. Sister, C., J. Wolch, and J. Wilson, 2010: Got green? Addressing environmental justice in park provision. *GeoJournal*, **75** (3), 229–248. https://doi.org/10.1007/s10708-009-9303-8

253. Mullenbach, L.E. and S.A. Wilhelm Stanis, 2022: Climate change adaptation plans: Inclusion of health, equity, and green space. *Journal of Urban Affairs*, 1–16. https://doi.org/10.1080/07352166.2022.2091449

254. Flores, A.B., T.W. Collins, S.E. Grineski, A.L. Griego, C. Mullen, S.M. Nadybal, R. Renteria, R. Rubio, Y. Shaker, and S.A. Trego, 2021: Environmental injustice in the disaster cycle: Hurricane Harvey and the Texas Gulf Coast. *Environmental Justice*, **14** (2), 146–158. https://doi.org/10.1089/env.2020.0039

255. Maldonado, A., T.W. Collins, S.E. Grineski, and J. Chakraborty, 2016: Exposure to flood hazards in Miami and Houston: Are Hispanic immigrants at greater risk than other social groups? *International Journal of Environmental Research and Public Health*, **13** (8), 775. https://doi.org/10.3390/ijerph13080775

256. Prudent, N., A. Houghton, and G. Luber, 2016: Assessing climate change and health vulnerability at the local level: Travis County, Texas. *Disasters*, **40** (4), 740–752. https://doi.org/10.1111/disa.12177

257. Smiley, K.T., I. Noy, M.F. Wehner, D. Frame, C.C. Sampson, and O.E.J. Wing, 2022: Social inequalities in climate change-attributed impacts of Hurricane Harvey. *Nature Communications*, **13** (1), 3418. https://doi.org/10.1038/s41467-022-31056-2

258. Collins, T.W., S.E. Grineski, J. Chakraborty, and A.B. Flores, 2019: Environmental injustice and Hurricane Harvey: A household-level study of socially disparate flood exposures in Greater Houston, Texas, USA. *Environmental Research*, **179**, 108772. https://doi.org/10.1016/j.envres.2019.108772

259. Collins, T.W., A.M. Jimenez, and S.E. Grineski, 2013: Hispanic health disparities after a flood disaster: Results of a population-based survey of individuals experiencing home site damage in El Paso (Texas, USA). *Journal of Immigrant and Minority Health*, **15** (2), 415–426. https://doi.org/10.1007/s10903-012-9626-2

260. Li, D., G.D. Newman, B. Wilson, Y. Zhang, and R.D. Brown, 2022: Modeling the relationships between historical redlining, urban heat, and heat-related emergency department visits: An examination of 11 Texas cities. *Environment and Planning B: Urban Analytics and City Science*, **49** (3), 933–952. https://doi.org/10.1177/23998083211039854

261. Atisa, G. and A.E. Racelis, 2022: Analysis of urbanization and climate change effects on community resilience in the Rio Grande Valley, South Texas. *Sustainability*, **14** (15), 9049. https://doi.org/10.3390/su14159049

262. Gutierrez, K.S. and C.E. LePrevost, 2016: Climate justice in rural southeastern United States: A review of climate change impacts and effects on human health. *International Journal of Environmental Research and Public Health*, **13** (2), 189. https://doi.org/10.3390/ijerph13020189

263. OWRB, 2012: Oklahoma Comprehensive Water Plan: Executive Report. Oklahoma Water Resources Board. https://www.owrb.ok.gov/ocwp/pdf/2012update/ocwp%20executive%20rpt%20final.pdf

264. Oklahoma Education, 2020: Oklahoma Academic Standards for Science. Oklahoma Education, 175 pp. https://sde.ok.gov/sites/ok.gov.sde/files/Oklahoma%20Academic%20Standards%20for%20Science.pdf

265. Puglisi, A. and J. Buitendag, 2022: A faith-based environmental approach for people and the planet: Some inter-religious perspectives on our Earth-embeddedness. *HTS Theological Studies*, **78** (2), 1–7. https://doi.org/10.4102/hts.v78i2.7582

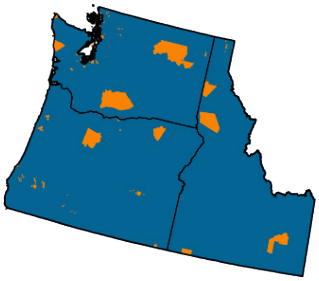
266. Jenkins, W., E. Berry, and L.B. Kreider, 2018: Religion and climate change. *Annual Review of Environment and Resources*, **43** (1), 85–108. https://doi.org/10.1146/annurev-environ-102017-025855

267. GCOOS, 2015: GCOOS Build-Out Plan—A Sustained, Integrated Ocean Observing System for the Gulf of Mexico: Infrastructure for Decision-Making. Gulf of Mexico Coastal Ocean Observing System. https://gcoos.org/wp-content/uploads/2020/04/BuildOutPlan-V2-updatedlogo-fin.pdf

268. Bender III, L.C., N.L. Guinasso Jr., J.N. Walpert, L.L. Lee III, R.D. Martin, R.D. Hetland, S.K. Baum, and M.K. Howard, 2007: Development, operation, and results from the Texas Automated Buoy System. *Gulf of Mexico Science*, **25** (1). https://doi.org/10.18785/goms.2501.04

Fifth National Climate Assessment: Chapter 27

# Northwest



# Chapter 27. Northwest

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# Introduction

The Northwest—Washington, Oregon, and Idaho—encompasses diverse communities, economies, and ecosystems, with almost 14 million residents.[1] From western coastal regions to forested mountains to arid shrub-steppe, the Northwest is home to numerous culturally and economically important native plants and animals. Northwest ecosystems provide housing, recreation, food, and income that support the collective health and well-being of the region's communities and economies. The 43 Federally Recognized Tribes in the Northwest also rely on the region's ecosystems to sustain their livelihoods. Climate change has already affected all areas in the Northwest and will continue transforming the region in consequential ways. Northwest communities are employing a variety of strategies to adapt to and prepare for climate change; however, there are limits to the long-term effectiveness of adaptation actions without comparable investments to mitigate climate change (KM 31.1).[2,3]

Climate change observations in the Northwest are consistent with projections from previous National Climate Assessments.[4,5,6] Annual average air temperatures in the region have risen by almost 2°F since 1900. Washington and Idaho have warmed by nearly 2°F, and Oregon has warmed by 2.5°F. Relative to 1900–2020, the annual number of extremely hot days and warm nights in the Northwest has been above the long-term average over the past decade, and the annual number of extremely cold nights over the same period has been below the long-term average.[7,8] By the 2080s, annual average temperatures in the Northwest are projected to increase by an average of 4.7°F under a low scenario (SSP1-2.6) and by an average of 10.0°F under a very high scenario (SSP5-8.5) relative to the period 1950–1999.[9] Future warming in the region is expected to exacerbate regional heatwave intensities (KM 27.5).[8,10]

Warmer winter temperatures have led to declines in mountain snowpack, particularly in areas with warm maritime climates.[11,12,13,14] A greater proportion of winter precipitation is projected to fall as rain rather than snow.[15] Warmer winter temperatures are expected to increase snow-line elevation, contributing to snow-dominated watersheds transitioning to mixed rain-and-snow watersheds and mixed rain-and-snow watersheds transitioning to rain-dominated watersheds.[16,17] Summer precipitation is projected to decline under all scenarios, although it will be variable,[9] contributing to more frequent, longer, and more severe regional drought conditions that increase wildfire risk and decrease water availability (KMs 27.2, 27.3).

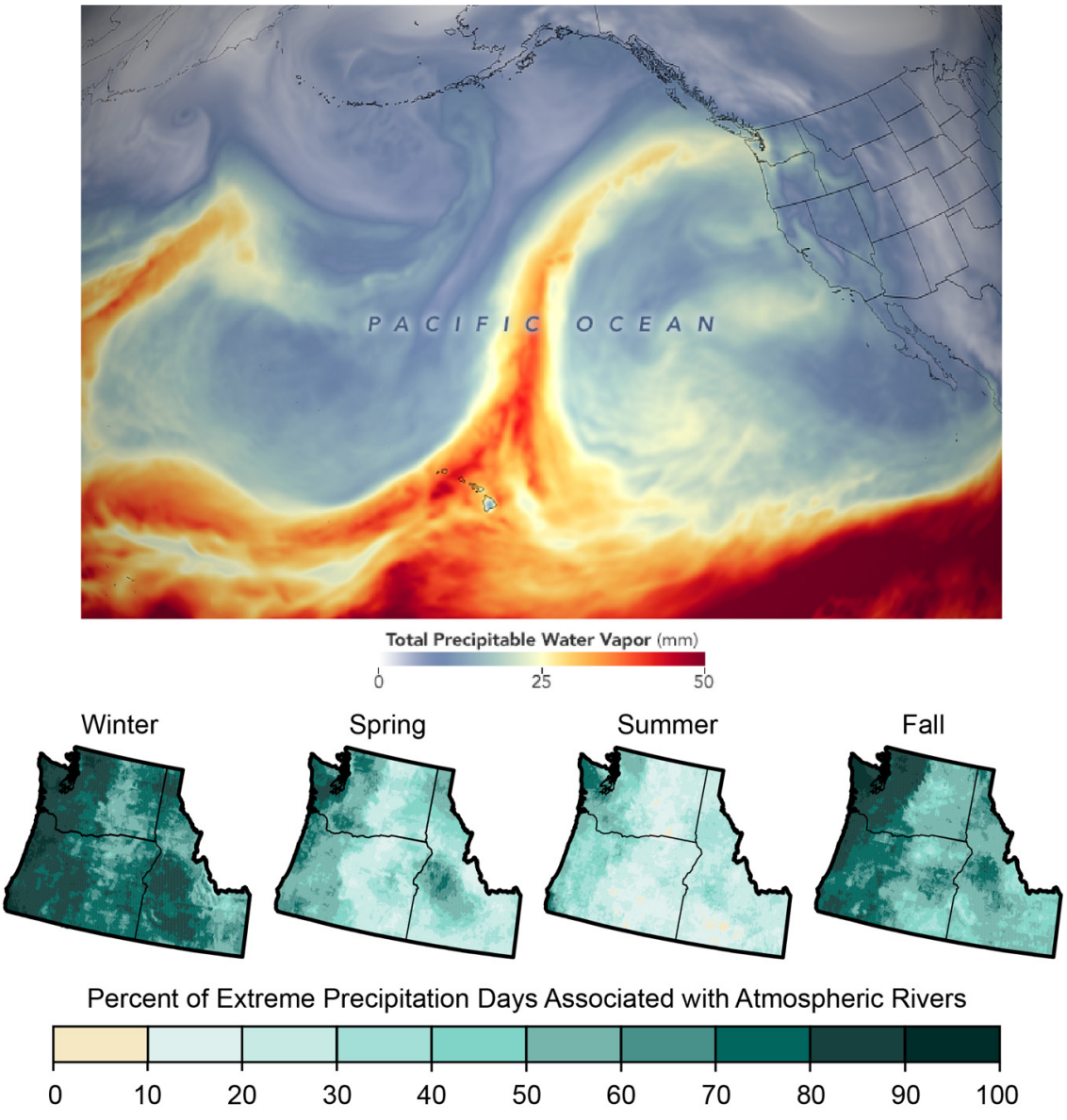
Interannual variability in precipitation is projected to persist, and observed lower streamflows in summer are expected to decrease even further due to reduced snow storage, increased evapotranspiration, and longer lags between summer precipitation events.[18,19,20] Increasingly low precipitation in drought years has driven extremely low streamflows.[20] Some currently permanent streams will transition to ephemeral streams, affecting aquatic species and regional water supply (KMs 27.2, 27.4).

Decreased snow accumulation and increasing melt are raising the elevation of the snow line, or the point at which annual accumulation and melt of snow are equal, which is causing Northwest glaciers to recede,[21,22] affecting recreation industries and regional water systems (KMs 27.3, 27.4, 27.6). Over the long term, streamflow reductions are expected in basins historically fed by glaciers.[23] Debris flows and landslides are expected to become more frequent as glacial recessions leave more bare land exposed to direct precipitation and the steep sideslopes of glaciated valleys are left unbuttressed by ice.[24]

The frequency and intensity of extreme precipitation events are projected to increase across the region.[7,8,25] Long, narrow bands of atmospheric water vapor transport, commonly known as atmospheric rivers (ARs), are associated with extreme precipitation in the western United States, where they contribute an average of 30%–45% of total winter precipitation (Figure 27.1).[26,27,28] ARs can cause severe damages,[29] such as the widespread damage resulting from ARs witnessed in western Washington in November 2021 (KM 27.4). A greater number of strong AR events and fewer moderate and weak events are projected to occur,[30]

although the changes in the frequency of landfalling ARs vary across climate models.[31,32] While the average contribution of ARs to annual precipitation in coastal areas is 50% or greater,[33] ARs are projected to reach farther inland.[34,35,36,37,38] Understanding how climate change affects ARs is critical to estimating how the region's water supply will change (KM 27.4).

## Atmospheric Rivers and Extreme Precipitation in the Northwest




**Extreme precipitation days are closely associated with atmospheric rivers, which are projected to be more frequent and intense and to reach farther inland.**

**Figure 27.1.** (**top**) Satellite imagery shows the total precipitable water vapor on February 6, 2020. Red areas indicate more precipitable water vapor, which appears in a narrow band known as an atmospheric river (AR) directed toward the Northwest. (**bottom**) ARs are closely associated with extreme precipitation events and vary across meteorological seasons, as seen by the percentage of extreme precipitation events during 1981–2016 associated with ARs: winter (December–February), spring (March–May), summer (June–August), and fall (September–November). Fall and winter months have a higher percentage of extreme precipitation days associated with ARs, particularly in coastal regions and regions west of the Cascades. (top) Satellite image: Joshua Stevens, NASA Earth Observatory; (bottom) adapted with permission from Slinskey et al. 2020.[27] ©American Meteorological Society.

Seasonal coastal upwelling causes nearshore sea surface temperatures off the Washington and Oregon coasts to be cooler than offshore surface temperatures, tracking temperature trends in the slower-warming deep water.[39] Nonetheless, annual average coastal sea surface temperatures in the Northwest have warmed approximately 1.2°F since 1900, and the northern California Current is projected to warm by an additional 4.6°–7.3°F by the end of the century under a very high scenario (RCP8.5), affecting marine species in a variety of ways (KM 27.2).[39,40,41,42] Human-caused carbon emissions have already driven ocean acidification of surface and subsurface waters off Oregon and Washington.[43] Synergies among ocean acidification, hypoxia, and human-caused nutrient inputs negatively affect many species, with cascading effects on food webs and human communities (KMs 27.2, 27.6).[44,45,46]

Two recent periods of widespread and persistent high sea surface temperatures in 2014–2016 and in 2019, known as marine heatwaves (and informally as the "Blob" and "Blob 2.0"), temporarily increased onshore temperatures by up to 11°F above regional averages,[47] resulting in short-term shifts in species distributions and mortality of many seabirds[48] and marine mammals (KMs 10.1, 27.2).[49] These heatwaves increased the toxicity of harmful algal blooms to marine mammals and humans who consume crabs and other shellfish (KM 27.6).[50,51,52,53,54]

Sea level is projected to increase across the Northwest under all scenarios (App. 3.3).[55] Net sea level changes vary by location in response to rising sea levels and vertical land motion, which is the long-term change in land surface elevation from processes such as tectonic forces (Table 27.1).[56] Sea levels are further affected by climate cycles, such as El Niño, which can raise sea levels up to another 7.9 inches for several months. Relative to the 1991–2009 average, relative sea levels in the Northwest are projected to rise 0.6 to 1.0 feet by 2050 for the Intermediate and High scenarios, respectively (Table 27.1),[55] placing physical structures and communities at risk (KMs 27.1, 27.4).[57] In Puget Sound, where most land is subsiding, sea levels are expected to rise 0.9 to 1.6 feet by 2050 and 3.2 to 10.2 feet by 2150 under a very high scenario (RCP8.5), relative to the reference period. On Washington's outer coast, sea level rise is anticipated to range from 0.1 to 0.8 feet by 2050 in Neah Bay, where land is rising, and 0.5 to 1.2 feet by 2050 in Tahola, where land is subsiding, under a very high scenario (RCP8.5).[58]

**Table 27.1 Sea Level Rise Projections for the Northwest**

Sea level rise is projected to increase across the Northwest under all sea level rise scenarios. This table illustrates the variability of sea level rise projections for 2050, 2100, and 2150 across the Northwest under the Intermediate and High sea level scenarios[55] and for specific locations under comparable scenarios (50% likelihood of exceedance and 1% likelihood of exceedance, respectively) for downscaled sea level rise projections for Washington State under a very high scenario (RCP8.5).[58] The changes are increases in feet, relative to the 1991–2009 average. See Appendix 3 for associated information on scenarios.

| Location | 2050 | 2100 | 2150 |
|---|---|---|---|
| **Northwest Region** | 0.60–1.03 | 2.64–5.98 | 5.40–10.86 |
| **Tacoma, WA** | 0.9–1.6 | 2.5–5.3 | 4.2–10.7 |
| **Neah Bay, WA** | 0.1–0.8 | 1.0–3.8 | 1.8–8.4 |
| **Tahola, WA** | 0.5–1.2 | 1.7–4.5 | 3.0–9.5 |

## Key Message 27.1

## Frontline Communities Are Overburdened, and Prioritizing Social Equity Advances Regional Resilience

Ongoing systemic oppression disproportionately exposes frontline communities in the Northwest—including low-income urban communities of color; rural and natural resource–dependent communities; and Tribes and Indigenous communities—to the consequences of extreme heat, flooding, and wildfire smoke and other climate hazards (*very high confidence*). Frontline communities often have fewer resources to cope with and adapt to climate change but have been leaders in developing climate solutions within and outside their communities (*high confidence*). Actions to limit and adapt to climate change that prioritize climate justice and redirect investments to frontline communities can advance regional resilience (*medium confidence*).

In the Northwest, a history of disenfranchisement and systemic neglect of specific populations has influenced their geographic and occupational exposure to climate-related hazards.[59,60] Long-lasting effects of settler colonialism, racially restrictive covenants, and exclusionary laws have pushed Indigenous communities, communities of color, and low-income communities into areas that are more vulnerable to climate change.[59,61,62]

Additionally, economic, political, and social systems play critical roles in distributing the costs and benefits of climate action (KM 20.3), limiting frontline communities' socioeconomic mobility and, thus, their capacity to adapt. As a result, these communities not only experience disproportionate climate burden but also have the fewest resources with which to respond and adapt to climate change.[59]

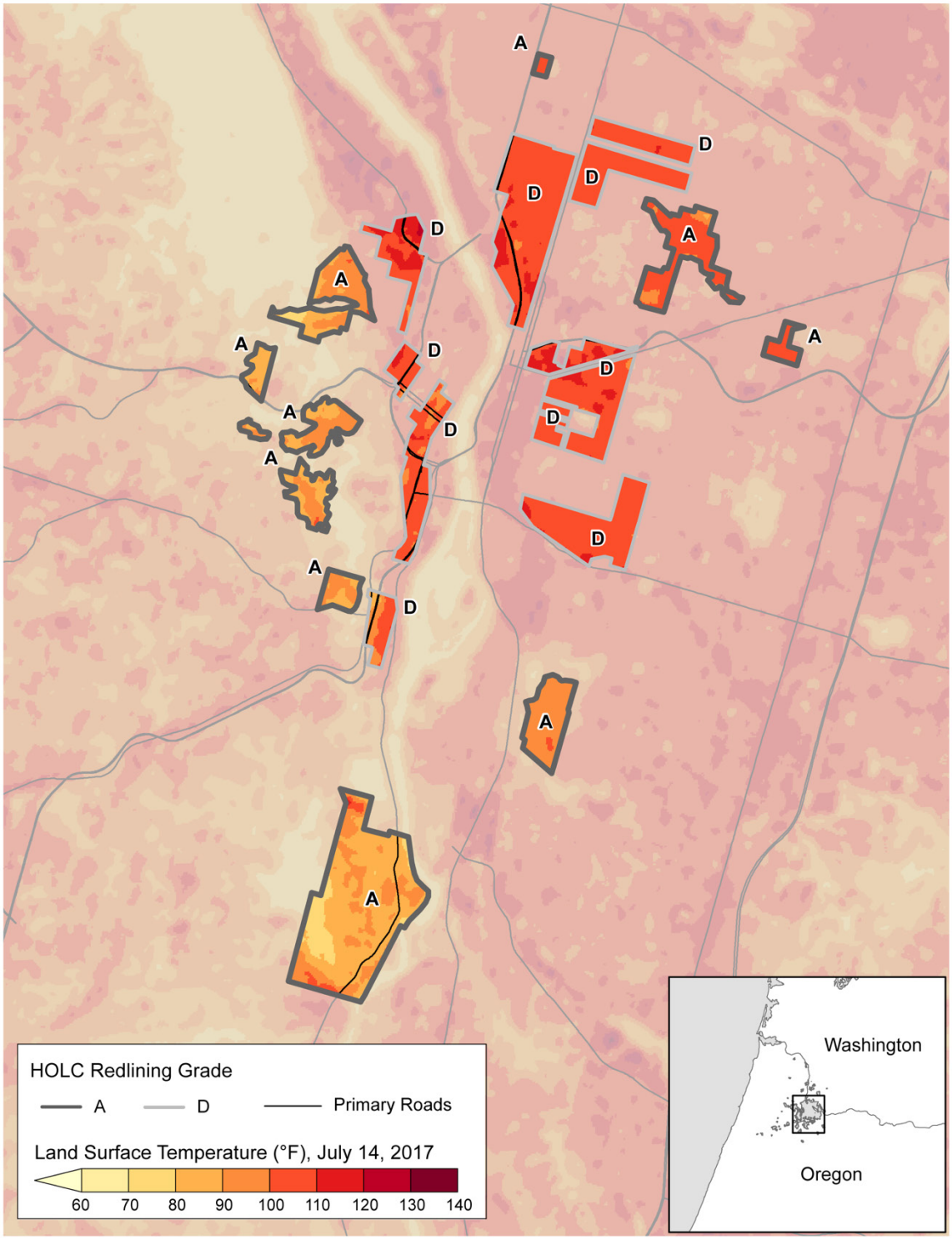
While many types of frontline communities exist—such as unhoused individuals, young children, older adults, and people with preexisting health conditions—this section highlights three communities: low-income urban communities of color, rural and natural resource–dependent communities, and Tribes and Indigenous communities.

### *Low-Income Urban Communities of Color*

Redlining, restrictive housing covenants, and other historical policies have reinforced racial and economic discrimination and exacerbated inequitable exposure to contemporary climate impacts (KM 20.3).[63] Formerly redlined communities in Portland, Tacoma, Seattle, and Spokane are still economically and racially segregated and continue to be deprived of equitable access to environmental amenities that protect against the consequences of climate change.[64,65,66] Formerly redlined areas can be up to 13°F warmer than the city's average surface temperature (KM 27.4), intensifying some impacts for residents such as heat exhaustion (Figure 27.2).[67,68] Incidences of heat-related illness and death are on the rise and are expected to increase as the climate changes.[69] Extreme heat poses the most consequential health risks for older adults, low-income households, outdoor laborers such as agricultural workers and construction workers, people who are unhoused, and others who have limited access to adaptive resources such as affordable cooling options (KM 27.5).

Previously redlined communities also have reduced diversity of plant and animal species due to land-use decisions that facilitated industrialization, reduced tree cover, and increased the severity of the urban heat island effect.[68,70,71] Furthermore, the same factors contributing to urban heat islands—a higher proportion of water-impervious surfaces and lack of green spaces—also increase the chances of urban flooding during extreme precipitation events.[72,73]

## Redlining and Extreme Heat in Portland, Oregon




**Economically and racially segregated urban communities are inequitably exposed to climate change impacts, including extreme heat.**

**Figure 27.2.** The map shows satellite-derived land surface temperature (in °F) for July 14, 2017. Areas in Portland, Oregon, that were historically redlined—that is, areas that received Home Owners' Loan Corporation (HOLC) grades of D, or "hazardous"—experience more intense heat island effects than areas that received HOLC grades of A or B. Residents are disproportionately exposed to extreme heat in these areas, where surface temperatures are up to 13°F warmer than the city's average surface temperatures.[68] Figure credit: Portland State University and NOAA NCEI.

## Rural and Natural Resource–Dependent Communities

Many rural communities depend on natural resources and therefore are particularly vulnerable to climate change (KM 27.3).[74] Workers in natural resource and outdoor-based industries will experience heightened exposure to heatwaves and wildfire smoke,[75,76] and outdoor construction workers face higher rates of traumatic injuries when exposed to extreme heat.[77] Washington and Oregon have high numbers of agricultural workers, especially Latino migrant workers, many of whom live in areas with low community resilience to climate-related hazards.

Structural inequities limit low-income, migrant, and agricultural workers' access to clean air and drinking water, adequate living conditions, healthcare, and other social services, compromising their ability to adapt to climate-related risks.[78] As natural resource economies adapt, shifts in the seasonal availability of work and the diversification of local economies yield both positive and negative outcomes, including new economic opportunities, improved equitable occupational health and safety policies, and job security for outdoor workers and rural communities.[79,80,81] Weather- and climate-service providers supply these communities with tools and resources—such as communication materials or user-friendly models—to help them be more resilient.[82,83,84] Effective climate services that are inclusive of diverse perspectives and communities that also contextualize extreme weather events within long-term climate changes can reduce maladaptation and improve community resilience to climate change.[3,74,85,86,87]

## Tribes and Indigenous Communities

Tribes and Indigenous communities experience disproportionate climate impacts and systemic barriers that limit their ability to adapt to climate change (KM 16.1).[88,89] Due to historical policies of land allotment, many landscapes have heterogeneous management across Tribal and non-Tribal jurisdictions, which can amplify wildfire or flooding risk to Tribal structures and limit the adaptation options for Tribal members. These policies complicate the ability of Tribes to access structures and spiritual locations during or after climate-related events.[90,91] For example, some coastal Tribes, such as the Quinault Indian Nation, are adapting to coastal flooding by reacquiring fractionated land to relocate housing and key facilities.[92] Even when Tribes manage contiguous areas of lands, limited access to funding, among other challenges, hinders planned or community-led relocation efforts (KM 9.3).[92,93]

Climate change also affects cultural and traditional foods and other resources, leaving Tribes without traditional sustenance and medicines for religious or ceremonial purposes (KM 27.6).[94,95] Climate change can shift resources outside usual and accustomed areas into adjacent non-Tribal jurisdictions or cause phenological shifts that affect cultural harvesting practices.[95] For example, shifts are expected in huckleberry habitat and the timing of huckleberry flowering and fruit ripening, affecting Tribes who rely on huckleberries for cultural and economic uses.[96]

## Climate Action and Social Equity

Climate solutions designed without input from frontline communities can result in maladaptation, increasing vulnerability and cost burden.[97,98] For example, measures to lessen the impacts of extreme heat, like green infrastructure, have increased real estate values in cities such as Portland and Seattle, a phenomenon known as green gentrification.[59,99,100] As utilities transfer the costs related to extreme events and the transition to renewable energy directly to consumers, utility bills are expected to become unaffordable for low-income households.[101] Inequitable adaptation exacerbates displacement risks for low-income urban populations and can lead to cascading development pressures in rural areas (KM 27.6).[102,103,104] The rising cost of living, alongside socioeconomic disparities, limits temporary relief and long-term recovery options for those who are affected by climate-intensified extreme weather events, such as the 2021 heat dome event.

In response to grassroots advocacy and community-led efforts, state and local climate policies in the Northwest are increasingly recognizing the importance of climate justice. These policies are prioritizing strategies such as subsidizing adaptation, redistributing benefits, and reducing harm to frontline communities.[105,106] Despite facing disproportionate risks from climate change impacts, frontline communities have emerged as leaders in climate action, elevating policies that center social equity and confer resilience to communities across the region.[97]

## Key Message 27.2

## Ecosystems Are Transitioning in Response to Extreme Events and Human Activity

Ecosystems are expected to change as the climate continues to change and as the magnitude and frequency of extreme events increases (*very high confidence*). Some historical and ongoing human activities reduce ecosystem resilience and the adaptive capacity of species (*very high confidence*). These human activities are expected to exacerbate many effects of climate change (*very high confidence*). Human efforts to enable ecological adaptation founded in ecological theory are expected to improve ecosystem functions and services and reduce exposure to climate-related hazards (*medium confidence*).

### *Ecological Effects of Climate Trends and Extreme Events*

Long-term changes in climate and the frequency and magnitude of extreme events, such as droughts, floods, and heatwaves, affect species and ecological processes (Figure 27.3).[107,108,109,110] High temperature records set in the Northwest from 2015 through 2021 were associated with many short-term or long-term ecological transformations, such as mortality or physiological damage to numerous native species of plants and animals, changes in water availability, and wildfire dynamics. Ecological effects and responses to climate change are not uniform, even among closely related species.[111,112]

## Impacts of Climate-Related Extreme Events on Northwest Ecosystems

**Long-term climate changes and extreme events threaten Northwest ecosystems.**

**Figure 27.3.** (**top**) Flooding on November 16, 2021, in the Nooksack River is shown. Flooding is expected to become more frequent and severe as a result of more intense rainfall and rain-on-snow events. (**middle left**) Non-native invasives such as the European green crab (*Carcinus maenas*) disrupt food webs as their distribution expands with warming coastal waters. (**middle center**) Postfire debris flows are expected to become more common with increased wildfire and precipitation intensity. (**middle right**) Large areas across the Northwest—such as in Idaho—are prone to increased risk of wildfires. (**bottom left**) Aspen is sensitive to high air temperature, leading to more dying aspen groves. (**bottom center**) Increases in the distribution and density of non-native invasive grasses, such as cheatgrass (*Bromus tectorum*), exacerbate wildfire risk. (**bottom right**) Seedlings are more sensitive than mature trees to heat stress and drought. Satellite image: (top) Lauren Dauphin and Joshua Stevens, NASA Earth Observatory. Photo credits: (middle left) ©Emily Grason; (middle center, middle right, bottom left) ©Charlie Luce; (bottom center) ©Erica Fleishman; and (bottom right) Colorado State Forest Service.

## Terrestrial Ecosystems

People in the Northwest rely on forests for diverse goods, services, and cultural purposes (KMs 7.2, 27.2). Warming temperatures and decreased summer precipitation over the past four decades have contributed to increases in the size and maximum elevation of wildfires in Northwest forests, and those trends are expected to continue.[113,114,115] Because concurrent heat and drought are becoming more common,[116] the volume of stressed or dead vegetation is increasing, which is increasing fuel load and wildfire risk. Across the western United States, many previously burned forests are reburning.[117] Some low-elevation and dry areas are converting from forest to shrubland after wildfires, and these transitions are expected to continue in the Northwest.[118,119]

In arid woodlands and shrublands throughout the Northwest, the distribution and abundance of non-native and highly flammable cheatgrass (*Bromus tectorum*) continue to increase before and after wildfires.[120,121] Cheatgrass establishment is associated with relatively high precipitation during autumn and spring[120] and with ground disturbance from wildfire, livestock grazing, and other types of land uses.[121,122] Changes in human activities such as recreation, development, transportation routing, and energy transmission will also continue to affect wildfire frequency (KM 27.4).[104] The length of the wildfire season and the potential for human-caused ignitions in all Northwest ecosystems are expected to increase as drought frequency, duration, and intensity increase.[123]

Climate change can affect the distribution and population dynamics of native and non-native species. When some non-native species become effective competitors with native and other non-native species, they are considered to be invasive in natural and human-dominated systems, including forests used for timber harvest or recreation. Some of these invasive species are expected to become more prevalent in response to projected increases in temperature, especially minimum winter temperature, and increases in the frequency, duration, and severity of drought across the Northwest.[117,124]

Additionally, some insects in the Northwest that harm or kill conifers are native herbivores that are prone to outbreaks. For example, densities of native mountain pine beetles (*Dendroctonus ponderosae*) generally are low, but outbreaks can result in 60% stand-level mortality over vast forest areas.[125] The Douglas-fir beetle (*Dendroctonus pseudotsugae*), another insect native to the Northwest, can damage both stressed and healthy Douglas firs (*Pseudotsuga menziesii*). The effects of outbreaks on trees generally are greatest during hot, dry summers when trees may be water-stressed.[126] Additionally, warm winters may decrease beetle mortality, increasing the likelihood of an eruption.[126,127]

## Aquatic Ecosystems

Hydrological and thermal changes will prompt shifts in species composition of native and non-native fishes, especially where their habitats have been impaired by land use, including stream modifications and water withdrawals.[128,129,130,131] For example, rising temperatures, disease spread, and competition threaten the native bull trout (*Salvelinus confluentus*) and cutthroat trout (*Oncorhynchus clarkii*).[132] Non-native invasive species such as smallmouth bass (*Micropterus dolomieu*), which thrive in warmer waters, continue to expand in the Columbia River basin, competing with and consuming native salmonids.[133,134] Increased intensity of precipitation and occurrence of rain-on-snow events will increase flood severity and frequency, endangering salmon eggs and juveniles.[135,136,137,138,139]

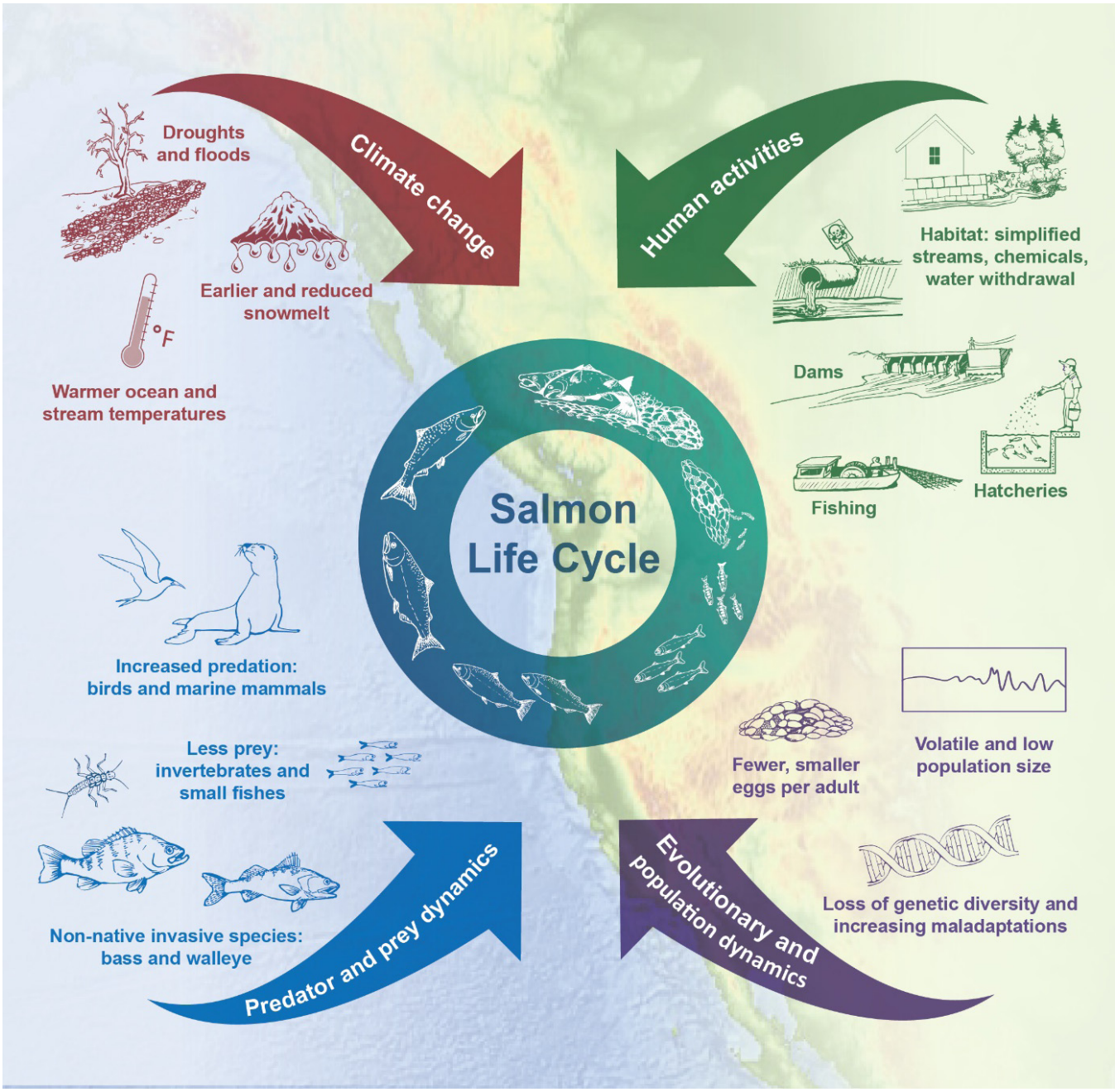
Increases in wildfire size and intensity are expected to lead to local extinctions of resident fishes,[140] warmer stream temperatures,[141] and increased sediment transport, turbidity, and fine sediments in streambeds.[142,143] Habitat connectivity can ameliorate local extinctions following wildfire and postfire debris flows, although local extinction can be permanent if habitat patches are small and are isolated by temperature or road culverts.[144]

## Coastal and Marine Ecosystems

The 2014–2016 marine heatwave had numerous effects in the highly productive California Current marine ecosystem,[145,146,147] including the first documented domoic acid poisoning of sea lions, with detectable levels of domoic acid in dolphins, whales, and seals off the Washington coast.[148] These toxins are now detectable year-round in sea lions, not just during algal blooms.[149] Changes in the ecosystem during the heatwave also caused mass mortality of seabirds, such as Cassin's auklets (*Ptychoramphus aleuticus*)[48] and common murres (*Uria aalge*)[150] and led to extensive closures of crab and shellfish fisheries.[54] Many salmon populations also contracted sharply after the heatwave.[151] Preliminary evidence indicates that, following extreme heat in June 2021, numerous shellfish species became thermally stressed or died.[152] The frequency and intensity of marine heatwaves are expected to increase.[153] These marine heatwaves are expected to have broad-ranging impacts on marine ecosystems[154] and increase the incidence of human–wildlife conflict, such as entanglement of whales in fishing gear.[155] While the impacts of future marine heatwaves on species will vary—some species will decline, others will increase, and others will shift their distributions—current regulations and practices may not adequately respond to these impacts, potentially leading to disruptions in fisheries (KM 27.3).[145]

Salmon abundance, age at maturation, and size at maturity are widely correlated with climate trends (Figure 27.4).[156,157,158,159] Idaho's Snake River spring and summer Chinook and sockeye salmon are at particularly high risk across multiple future temperature scenarios (Box 27.1).[160,161,162,163,164,165] Increasing temperatures are expected to increase the duration and spatial extent of enabling conditions for harmful algal blooms,[166,167] increasing threats to marine mammals, fish, and shellfish. Population instability increases volatility in fisheries and the extinction risk for species that are already at low abundance.[168,169]

## Interacting Stressors Affecting Salmon Resilience




**Stressors stemming from interactions between human activities and natural systems affect freshwater and marine ecosystems and reduce salmon resilience to climate change.**

**Figure 27.4.** Human activities and climate change alter the physical environment in concert, often amplifying their impacts through cumulative effects over the salmon life cycle. They also directly and indirectly alter freshwater and marine systems. Natural systems respond to changes in their environment through both evolutionary and ecological processes. The sum of these many different processes has led to declines in many populations of salmon over decades and reduced their ability to cope with future climate change. Figure credit: NOAA Fisheries.

## Box 27.1. Snake River Sockeye Salmon

Snake River sockeye salmon, an important species for the region, is highly vulnerable to climate change.[161,170,171,172] Application of conservation genetics and interagency and Tribal cooperation[173,174] have sustained this culturally and ecologically unique population.

Over 150 years, a variety of human activities have affected Idaho sockeye. For example, overfishing, construction of dams that blocked migration for periods of time, and stocking of non-native fish populations altered aquatic ecological processes in complex ways.[175] Numerous factors contributed to sockeye declines until almost no fish returned from the ocean in the 1990s. All 16 adults known to have returned during that decade were captured and taken into a breeding program.[176,177] Subsequently, a collaboration among federal, state, and Tribal biologists increased reproduction of the captive fish, allowing the release of smolts and some adults to the wild to spawn. In 2014, a peak of 1,579 sockeye salmon returned to Idaho's Sawtooth Mountains.[151]

In July 2015, a record-breaking heatwave combined with low snowpack from the previous winter led to high water temperatures that killed nearly all naturally migrating adults, highlighting the vulnerability of this life stage in sockeye salmon.[161,178,179] To protect genetic diversity in hot years and maximize reproductive capacity, adults have been collected at dams and transported upriver nearly 500 miles. By the 2040s, temperatures in the free-flowing Salmon River, which travels 425 miles in central and eastern Idaho, could rise several degrees more than larger rivers downstream under SRES A1B and B1 scenarios (similar to intermediate and high scenarios). The Salmon River could lose nearly half its streamflow during the adult migration window, threatening this endangered species.[161] Extensive water withdrawals and habitat modifications in the Salmon River basin[171,180,181] exacerbate these conditions. Nevertheless, the quality of juvenile rearing habitat[182] and marine survival[174] are relatively high in this population, and reintroduction programs are widely supported.[183] Additional actions to restore cool, clean water throughout the basin would support the population's natural adaptation to climate change.[181,184,185]

## *Ability of Ecosystems and Species to Adapt to Climate Change*

Historic and contemporary land use interacts with climate change to affect species' adaptive capacity—their genetic, physical, and behavioral ability to respond to environmental change.[186,187] Many different strategies to adapt and build resilience within Northwest ecosystems include ecological protection and management, assisted migration, market-based mechanisms, and conservation of genetic diversity.[188,189,190]

Protection and restoration of natural water bodies and processes that maintain water availability and quality can offset some effects of land use, including the growing demand for irrigation that reduces streamflow and freshwater habitat quality.[16] Similarly, modification of natural or built flood-control structures can reduce adverse downstream effects of changes in hydrology, sedimentation, and shoreline erosion and improve water quality and capacity for groundwater drainage in agricultural systems.[191] These efforts can lead to cascading benefits for habitats, supporting salmonids, other fishes, shellfish, and shorebirds.[192,193]

Restoration of floodplains that provide habitat for salmon[194] also benefits humans by reducing the current and future exposure of agriculture and infrastructure to flooding from the combined effects of higher sea levels, storm surge, and stream runoff.[195,196] As several dams and other barriers to historical spawning areas have been removed in recent decades, fishes have rapidly recolonized newly accessible habitat in some cases.[197,198,199,200]

Reintroduction of fire and thinning of non-fire-resistant vegetation reduce wildfire severity and risk in some Northwest forests and woodlands, especially dry forest types where vegetation has accumulated due to past fire exclusion policies.[201,202] These forest management practices also have the potential to reduce drought-related mortality.[203] Burning and forest thinning may not decrease wildfire severity and risks in wet or cold forest types[204,205] but can increase plant and animal diversity.

Wetlands offer some protection against extreme weather events.[206] Wetland mitigation banks create or enhance wetlands in a given location as compensation for loss or degradation of other wetlands. The number of these banks has increased across the region,[207] but long-term evaluations of created wetlands[208] or the effectiveness of wetland mitigation banks[209] are uncommon. Market-based approaches, such as temporary water-right leases or permanent transfers, have the potential to support ecosystem functions, such as instream flow augmentation for fish health, with payments to users of competing resources.[210] However, market and political bottlenecks affect the efficacy of these approaches.[211]

The ability of species to adapt to climate change is varied, and the likelihood of adaptation depends in part on the amount of genetic variation in a population or species, which is often related to the number of individuals and their relatedness.[188] Evolutionary responses to recent climate change have generally been less than what might be expected, and these constraints are not fully understood.[212,213] The feasibility of quantifying abundance, relatedness, and genetic variation varies among populations and species, and these measures have not been estimated for many populations and species.

## Key Message 27.3

## Impacts to Regional Economies Have Cascading Effects on Livelihoods and Well-Being

Climate change impacts to the Northwest's natural resource- and outdoor-dependent economies will be variable, given the diversity of industries, land cover, and climatic zones (*very high confidence*). Impacts to these industries will have cascading effects on community livelihoods and well-being (*high confidence*). While some industries and resource-dependent communities are resilient to climate-related stresses, economic responses to climate change can benefit affected industries, workers, and livelihoods (*medium confidence*).

### *Agricultural Industries and Livelihoods*

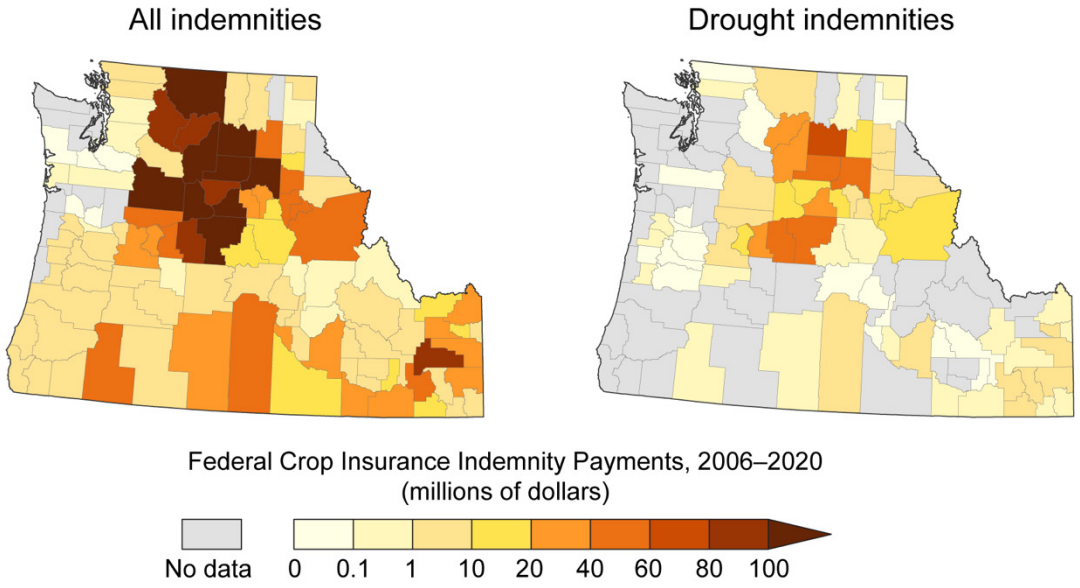
The Northwest encompasses 138.8 million acres of public and private cropland, grassland, pasture, rangeland, and forests,[214] and agricultural production totaled $6.28 billion in 2021 (in 2021 dollars).[215] The agricultural economy includes farms and ranches that have been in operation for multiple generations and is dependent on a seasonal migrant workforce, mostly from Mexico and Central America (KM 27.1).

Climate change affects crop production quantity and quality, and multiple competing effects depend on crop and region, causing increases and decreases in projected yields (Box 27.2; KM 11.1).[216] Chill accumulation—exposure to cold temperatures during dormancy—is key for fruit set and fruit quality in perennial crops and is expected to decrease in the southern parts of the Northwest and increase in the northern parts.[217] Increased exposure to extreme temperatures can induce cosmetic effects (e.g., sunburn in apples) that make crops increasingly unmarketable.[218] Pest pressures are expected to increase due to climate change; however, preliminary research indicates that the efficacy of non-chemical control of pests can also increase, providing opportunities for reduced pesticide use and environmental benefits.[217] Warmer autumns have been linked to potential increased risk of honeybee (*Apis mellifera*) colony failure in the following spring even in the absence of other stressors,[219,220] thereby affecting the specialty crop industry that relies on managed honeybees. While increasing temperatures in some regions may present new economic opportunities, such as winegrape growing in Puget Sound,[221] other climate-related impacts such as wildfire smoke may impede these emerging industries.[222]

Drought conditions have also affected the region's agricultural lands and rangelands. Across the region, the 2021 drought resulted in reduced access to irrigation water and yield loss for several crops.[223] Significant yield declines between 2020 and 2021 in winter wheat, spring wheat, and barley were also attributed to drought.[224] Droughts have also decreased forage availability and productivity, affecting livestock operations and management of habitat for other species.[225] Market approaches such as temporary leasing of water can alleviate drought impacts on agricultural productivity and the regional economy to a certain extent.[226] Similarly, grass banks, which allow landowners to lease forage space for ranchers in exchange for implementation of conservation projects by ranchers, can allow ranchers to better manage forage shortages caused by drought and are gaining popularity in the western United States.[227,228]

Increasing trends in crop insurance loss payments—an indicator associated with economic disruption of agricultural production due to extreme events and impacts—reflect the region's warming temperatures and declining snowpack (Figure 27.5).[229,230] Agricultural producer perceptions of climate risk affect the efficacy of place-based adaptation and resilience efforts, and operations that adapt to extreme weather and changing climate conditions may see improved productivity and resilience (KMs 6.1, 27.1).[3,82,83,87,231]

### Agricultural Losses Through Crop Insurance Indemnity Payments




**Increasing trends in crop insurance loss payments reflect the economic disruption of agricultural production due to extreme events including droughts.**

**Figure 27.5.** These county-level maps compare all crop insurance indemnity payments from the US Department of Agriculture Risk Management Agency (**left**) with those specifically due to drought, from 2006 through 2020 (**right**). All indemnity payments reflect both biophysical and socioeconomic impacts from weather- and climate-driven events, including major droughts, on important commodities such as wheat and potatoes. Figure credit: USDA. See figure metadata for additional contributors.

## *Forest Industries and Livelihoods*

Northwest forests provide multiple ecosystem and economic services. Rising temperatures and increased frequency of ecological disturbances may affect forest structure and growth (KM 27.2),[232] leading to reductions in the quantity and quality of forest products and commercially important timber species.[233,234,235,236] For example, these impacts could lead to the increase in density and distribution of ponderosa pine at higher elevations in the Blue Mountains ecoregion and the expansion of western Cascade

Range Douglas fir into higher elevations, affecting timber supply and carbon sequestration potential.[234,237,238] Dry coniferous forests and woodlands in lower to middle elevations—such as those on the east side of the Cascade Range, the Palouse Prairie–forest ecotone in Idaho, and drier areas of the Rocky Mountains—will experience large increases in wildfire frequency, extent, and severity, threatening forest and timber management initiatives.[117,239,240]

Climate impacts to forest industries will affect the livelihoods of communities dependent on timber and non-timber forest products.[234,237] While rural timber-based economies face additional economic risks from wildfires and drought, they also have local knowledge and insight to effectively reduce some of these risks (KM 27.1).[241] Despite this, climate impacts to forest product industries can lead to economic depression within some communities, resulting in migration away from these communities (KM 27.6).[241] However, localized species shifts could induce industries and private landowners to make new financially beneficial adaptation choices.[235,242] Other emerging opportunities, such as cross-laminated timber, can support local timber economies while providing sustainable and less carbon-intensive alternatives for construction.[243]

Reforestation and afforestation are expected to benefit ecosystem functions, such as increasing water quality, long-term carbon storage capacity, and viability of some native species (KM 7.2).[244] Tribal forest enterprises use harvest and conservation techniques reliant on Indigenous value systems to support improved forest management.[245] For example, the Confederated Tribes of the Colville Reservation are employing innovative drone technologies to conduct forest inventories, enabling them to improve their forest and timber management efforts, air and water quality, wildlife habitat, preservation of cultural areas and practices, and carbon sequestration potential.[246]

## *Commercial Fisheries and Livelihoods*

Climate change has affected fisheries in the Northwest (KMs 27.2, 10.2). Marine heatwaves and harmful algal blooms have led to climate-induced fishery losses on the West Coast, accounting for a $641.1 million (in 2022 dollars) reduction in commercial fishing revenue.[247] Climate change can also intensify stressors such as decreasing catch and landing rates and accelerating the graying of the fleet phenomenon—the increasing average age of commercial fishers.[248,249] Fishery losses and closures can affect fishing-adjacent industries, such as hospitality, and the cultural identity of residents who directly or indirectly rely on fishing.[250]

Tribes account for over half of federal fishery loss requests.[247] Further population declines, especially of Pacific salmon, will have additional consequences for Tribal communities reliant on fish for subsistence, ceremonies, and health.[95,251] Ocean acidification, hypoxia events, and algal blooms are also hurting Tribal Dungeness crab fisheries.[252] It is not always feasible for Tribes to secure loans and equipment and to thrive in competitive market systems. However, many Tribes are utilizing Indigenous approaches and Tribal–federal partnerships to increase the resilience of their commercial and subsistence fisheries.[253]

## *Tourism, Recreation, and Customer Service Industries*

The outdoor tourism and recreation industry in the Northwest supports $51.9 billion (in 2022 dollars) in annual expenditures and employs more than 588,000 individuals.[254] The economic impacts of climate change on the recreation industry will vary.[79] The snow season is projected to decrease by nearly half by the end of the century in parts of the Cascade Range.[255] Snow-based recreational industries such as skiing have already lost revenue due to the decrease in snow days, and future impacts to snowpack are expected to further harm snow-based recreational industries.[256,257] In contrast, earlier spring snowmelt and increasing temperatures can increase access to hiking trails and campgrounds, thereby extending these seasons. However, a regional shift from a snow- to a rain-dominated system (KM 27.6)[16,258] may present new operational and maintenance challenges from increased flooding and erosion.[259] Recently burned areas

typically are closed as a safety precaution, and poor air quality from wildfire smoke can deter outdoor activities and recreation.[79,260]

Higher temperatures may increase the demand for water-based and warm-weather activities such as boating, cycling, and fishing (KM 27.6).[79,261] For example, economic gains for cycling activities in Washington are expected to increase due to the declining numbers of cold days.[262] However, climate change can reduce the quality and aesthetics of recreational sites, affecting user preference and leading to reduced visitation rates.[79]

Changes in recreation management may produce inequitable outcomes. Rising costs to access recreation sites and limited ability to travel to alternative destinations will disproportionately affect low-income visitors. Increased cost of living in high-amenity areas such as ski resort towns will also stress workers and adjacent communities (KM 27.6).[263] Outdoor activities such as skiing and hiking can improve overall health and thereby reduce healthcare costs; however, decreased access to such activities can lead to increased risk of chronic diseases, mental health impacts, and loss of cultural heritage and connection to place (KM 27.6).[264]

## Box 27.2. Tribal Agricultural Economies Are Adapting to Climate Change

Northwest Tribal economies are diverse, and many are affected by climate change. Tribes are utilizing innovative approaches that braid Indigenous and Western sciences together to respond to these challenges.

Climate change is affecting Tribal agriculture.[265] The Nez Perce Tribe is currently working with non-Tribal managers to pilot regenerative agricultural practices that integrate Traditional Ecological Knowledge to improve economic, ecological, and cultural resilience.[266] The Yakama Nation is reacquiring agricultural lands to promote food sovereignty and to train the next generation's Tribal members in sustainable and regenerative farming.[267,268]

### *Just Transition and Community Livelihoods*

As local economies in the Northwest shift to low-carbon industries and climate-adaptive practices, historically overburdened workers will face higher exposure to climate-related hazards as well as risks of being excluded from economic shifts to a green economy (KM 27.1).[76,97,269] Local governments, Tribes, labor unions, and community groups across the region are evaluating and adopting policies and programs that support a just transition (KM 20.3).[97] Efforts toward a just transition in the Northwest region include investments in low-carbon sectors, local economic diversification plans, training and skills development for workers in resource-dependent and fossil fuel–dependent industries, financial assistance for impacted communities, and worker protections.[270,271] Despite progress in specific sectors, efforts that account for historically overburdened workers can reduce potential livelihood disruptions caused by economic shifts associated with decarbonization.[97,272]

## Key Message 27.4

## Infrastructure Systems Are Stressed by Climate Change but Can Enable Mitigation and Adaptation

Recent extreme events have stressed water systems and housing, transportation, and energy infrastructure across the Northwest (*very high confidence*). Extreme precipitation, droughts, and heatwaves will intensify due to climate change and continue to threaten these interrelated systems (*very high confidence*). Given the complexity of and interdependencies among infrastructure systems, an impact or a response within one sector can cascade to other sectors (*very high confidence*). Cross-sectoral planning, which can include redesigning aging infrastructure and incorporating climate considerations into land-use decisions, can increase resilience to future climate variability and extremes (*high confidence*).

Infrastructure systems are threatened by extreme events such as drought, wildfire, heatwaves, floods, and landslides (KM 12.2).[273] Climate change has revealed vulnerabilities in infrastructure planning and design, which are typically based on historical conditions and do not account for recent increases in the frequency or severity of extreme events. Isolated communities and those without alternatives if infrastructure fails are among the most vulnerable. Designing resilient infrastructure requires accounting for interdependencies among the built environment's physical and social elements.[274,275,276]

### *Water Infrastructure*

Droughts in the last decade in the Northwest demonstrated water supply vulnerabilities, such as depletion of reservoirs across central and eastern Oregon and southern Idaho.[277,278] Some water sources, infrastructure, and operations that treat and convey water were resilient during these droughts. However, some water providers were forced to access alternative sources, institute mandatory or voluntary conservation measures, or otherwise modify their operations. Small rural water providers are vulnerable because they usually depend on a single water source or sources with limited capacity and because operators generally have limited resources for planning, upgrades, and emergency response (KM 27.1). Wildfires in 2020 and 2021 damaged physical elements of the water delivery and treatment systems, disrupted electricity systems, and increased the amount of sediment in waterways and reservoirs.[142,279] These vulnerabilities will increase as droughts and wildfires become more frequent and severe.

About 30% of Northwest households use septic systems to treat their wastewater.[280] Sea level rise, high temperatures, extreme precipitation, and high streamflows reduce the function of septic systems.[281,282] For example, saturated soils impede wastewater treatment in drainfields.[283] Failures of wastewater storage and treatment will negatively affect human health and increase nitrogen loads in waterways.[284]

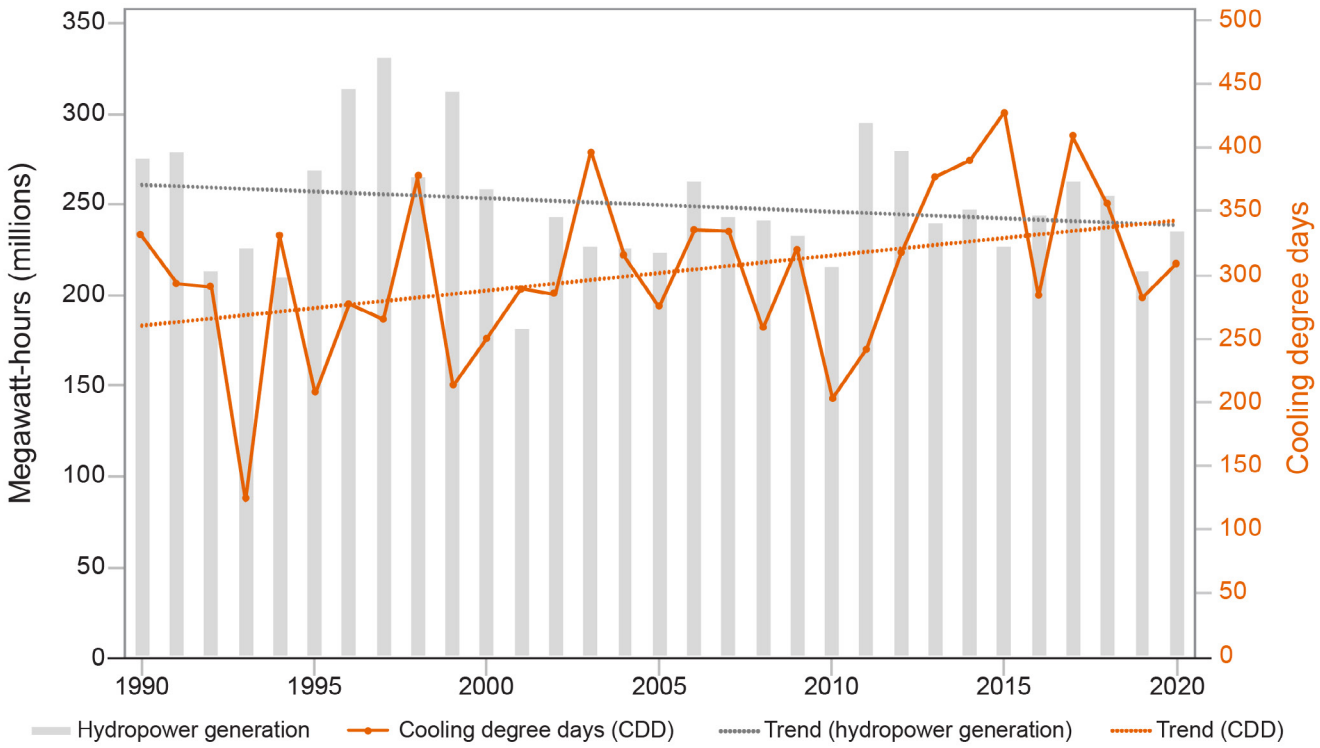
Emerging data and technologies can make drinking water and stormwater systems more resilient to climate change. For example, projections of changes in storm duration, intensity, and frequency[285] provide information needed to upgrade stormwater systems to reduce stresses from extreme precipitation.[286,287] Water utilities can reduce water losses during delivery and alleviate stress to the system during hotter summers and more severe droughts by upgrading distribution lines and minimizing water losses during treatment.[288] Water-efficient appliances, sprinklers with soil moisture sensors, drought resilient plants, and conservation education and incentives can also reduce water demand.[288]

## *Energy Infrastructure*

Climate change impacts nearly every aspect of the energy system, with interdependencies and cascading effects in other critical sectors (KMs 5.1, 12.2, 31.1; Focus on Compound Events). For instance, less snow, earlier snowmelt, and more frequent and intense droughts will alter the seasonal capacity of hydropower, a primary source of regional energy, to meet electricity demand.[278,289,290,291] Earlier snowmelt is also increasing the need for water storage in Idaho reservoirs.[11] Removal of dams may support salmon recovery but can reduce resilience in the regional power system (Box 27.1).[292]

Increasing temperatures and heatwaves are shifting the seasonal timing and spatial footprint of electricity demand.[291,293] Cooling degree days, a metric associated with energy demand for cooling, are increasing across the Northwest, and the region's population increases will also affect the electricity demand, potentially leading to energy shortfalls (Figure 27.6).[294] Population growth and droughts are expected to amplify competing claims to the water supply by irrigators, Tribes, power plants, and other water rights holders,[295,296] highlighting the interdependencies of energy, water, and agricultural systems. Strategies such as demand-side management (voluntarily shifts in power loads) and ongoing additions of solar power, such as that being pursued by the Nez Perce Tribe,[297] can increase the resilience of energy infrastructure.

### Annual Cooling Degree Days Relative to Annual Hydropower Generation




**Hydropower generation is currently meeting the number of cooling degree days but might not continue to do so as temperatures and heatwaves increase in the future.**

**Figure 27.6.** Cooling degree days—the annual cumulative number of days on which the average temperature is greater than 65°F—are typically used to measure cooling energy demand. During 1990–2020, the annual number of cooling degree days (orange lines) increased, whereas annual hydropower generation (in millions of megawatt-hours, gray bars) decreased slightly. Hydropower generation may not meet projected future cooling demand, especially during summer. Figure credit: Boise State University and Cascadia Consulting Group.

Electricity transmission and distribution grids are both a source of wildfire risk and are also at risk from wildfire, particularly in hot, dry, and windy conditions. Electric utilities and land management agencies are evaluating potential actions that they can take to reduce future wildfire risk and impacts on electricity systems (Box 27.3). Some Northwest electric utilities are exercising public safety power shutoffs or "fast trip" programs that trigger outages when faults are detected.[298] Such shutoffs can reduce the likelihood of ignitions from the electric grid when complemented by other risk-mitigation measures but can also negatively affect local economies and human health (Focus on Western Wildfires). Risks to electric grid infrastructure from wildfires may also be higher in remote areas, as monitoring capacity is less robust.

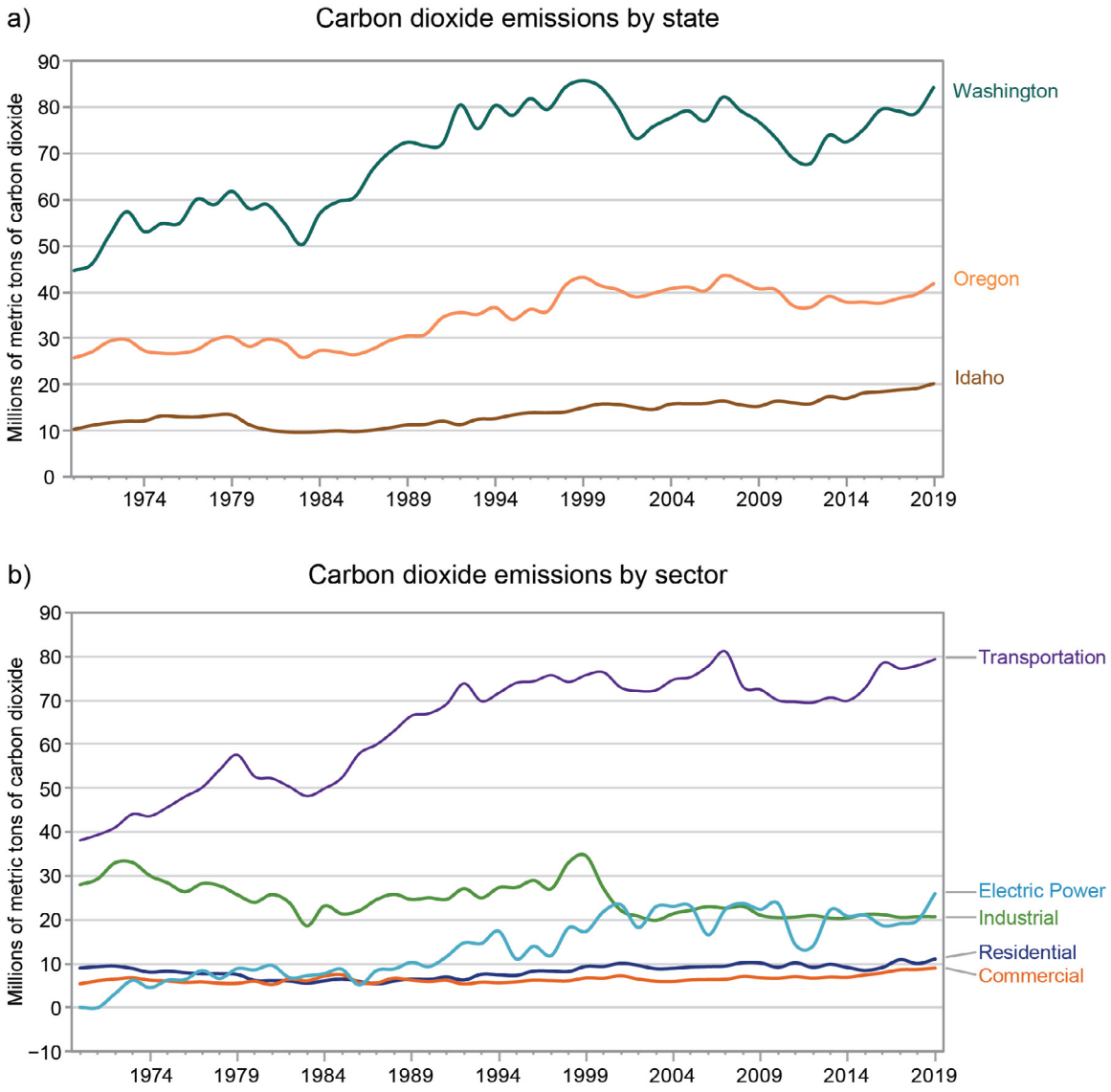
## Box 27.3. Washington State's Electric Utility Wildland Fire Prevention Task Force

Many states, including those in the Northwest, are taking new action on climate-related challenges for critical energy infrastructure. For example, in response to western wildfires in 2019 ignited by electricity transmission lines or that temporarily reduced electric services, the Washington State Legislature convened the Electric Utilities Wildland Fire Prevention Task Force[299] with the intent of increasing electricity infrastructure resilience through improved coordination across agencies and information sources. The task force advised the Washington State Department of Natural Resources on vegetation management, communication protocols, and investigation protocols related to wildfire risk and electricity reliability. The three outcomes of the task force's work were a model agreement for managing vegetation outside rights-of-way, protocols for coordinated investigation of wildfires that interact with utilities, and coordination of annual information exchanges among land managers, utility operators, and wildfire experts.

Carbon emissions have been increasing on an absolute basis in the Northwest (Figure 27.7). The shift to low-carbon energy systems can be complex, and there are varied trade-offs and co-benefits between technological innovations that can enhance the viability of clean energy sources and increase the resilience of both infrastructure systems and the communities and industries dependent on them (KM 5.3).[300,301]

Transitions to low-carbon energy may be perceived as requiring substantial time to accomplish, yet research has shown that considerable low-carbon transitions can occur in less than 15 years.[302] Considering these conditions, states, local governments, and utilities have begun to develop low-carbon and decarbonization plans and pathways. Oregon passed legislation to eliminate carbon emissions from the power grid by 2040, and Washington passed legislation to reduce carbon emissions by 95% from 1990 levels by 2050. In Idaho, cities such as Boise and utilities such as Idaho Power have carbon reduction plans.[105,303] Agencies and utilities are utilizing diverse strategies including energy conservation and efficiency investments; design approaches such as buildings with southern-facing windows to reduce cooling needs; harnessing renewable gas from farms and municipal landfills; and exploring and utilizing alternative energy sources while investing in decarbonization technologies.[300,304,305,306]

## Carbon Dioxide Emissions from Fossil Fuels by State and Sector




**Carbon dioxide emissions from fossil fuel consumption vary widely by sector and state.**

**Figure 27.7.** These graphs show carbon dioxide ($CO_2$) emissions (in millions of metric tons) from fossil fuel consumption by state (**top**) and sector (**bottom**). Carbon dioxide emissions from fossil fuel consumption are greatest in Washington, followed by Oregon and Idaho. Transportation emits more $CO_2$ than other sectors across Idaho, Oregon, and Washington. Figure credit: Boise State University and Cascadia Consulting Group.

## *Transportation Infrastructure*

Atmospheric rivers in 2021 illustrated existing understanding of how landslides and flooding can disrupt transportation routes.[307,308] The disruption of transportation routes can lead to injury or death due to a lack of evacuation routes and cutoff from critical emergency services, healthcare, and other goods and services.[29,309] In extreme cases, the loss of transportation routes and social services may displace households and reduce regional labor supply.[310] Much of the Northwest's transportation infrastructure, such as railroads, bridges, and highways, is aging and thereby increasing vulnerability to climate-related hazards. For example, the average age of all surveyed bridges in Oregon is 46 years old, and the typical design life is

75 years.[311] Some state transportation agencies, such as Washington State Department of Transportation and Oregon Department of Transportation, have assessed climate risks to their routes and highways and various adaptation options (KM 13.1).[312,313]

Transportation is the largest source of greenhouse gas emissions in the Northwest (Figure 27.7), and utilities and transportation agencies across the region are exploring electrification options to reduce emissions. However, efforts to electrify the transportation sector will increase electricity demand and place additional stress on the regional energy system (KM 13.1).[314,315,316] Electric vehicles' energy efficiency and electricity sources will affect the potential magnitude of reduction in transportation-related emissions (KM 13.4).[314,316]

## Housing and Land Use

The majority of the land in urban areas is devoted to residential housing, which provides shelter to people during extreme events but can also exacerbate exposure to harmful impacts. The specific location of urban housing structures can directly affect the severity of local climate impacts. Urban areas are warmer than their surrounding landscapes, a phenomenon known as the urban heat island effect, and some urban neighborhoods can experience temperatures upwards of 13°F warmer than other areas of the same city (KMs 27.1, 12.2). Residential density in urban areas is increasing more in historically lower-income neighborhoods, reducing the availability of green space and increasing the extent of impervious surfaces, thereby worsening heat island effects.[68,100] Urban trees and other vegetation could provide shade, but there are trade-offs between mitigating heat islands and conserving water.[317] Creating incentives or requirements for water-efficient landscaping (xeriscaping) while also providing shade and stormwater absorption could help reduce adverse impacts from extreme heat and storms.

Similarly, the location of housing beyond urban centers also interacts with the impacts from climate change. For example, housing in the wildland–urban interface (WUI)—or locations where wildland vegetation and houses meet—has increased over the past several decades and increases the risk of wildfire impacts on housing structures (KM 27.6).[102,318]

Furthermore, the quality of materials and types of amenities in both urban and rural housing design and construction affect exposure to some impacts, such as wildfire smoke. Households with access to HVAC and air filtration systems can improve indoor air quality and reduce wildfire smoke exposure;[319,320] however, they may be insufficient to mitigate anticipated increases in the number of wildfire smoke days and associated high concentrations of fine particulate matter and other pollutants.[321,322]

Climate change will also affect digital infrastructure, such as internet infrastructure systems. For example, fiber conduits and nodes in the greater Seattle area are at risk of inundation from sea level rise by the 2030s,[323] jeopardizing telecommuting strategies that some jurisdictions are using to reduce vehicle-miles traveled by employees and associated transportation-related emissions.

Because land-use laws determine how human activity is distributed in space and how infrastructure is built, they affect mitigation of and adaptation to climate change.[324] While each state has a different set of land-use policies, state-level land-use planning guidelines can limit or expand opportunities for local land-use plans to respond to climate change (KMs 6.2, 12.3). Nevertheless, land-use laws and policies can facilitate adaptation in multiple ways, including protection (protecting existing structures from climate-related hazards via engineered structures), accommodation (continued use in hazardous locations, like flood zones, by improving design or development standards such as raising foundations or creating natural floodplains), or retreat (restricting new development in hazardous locations).[324,325,326,327]

## Key Message 27.5

## Climate Change Amplifies Health Inequities

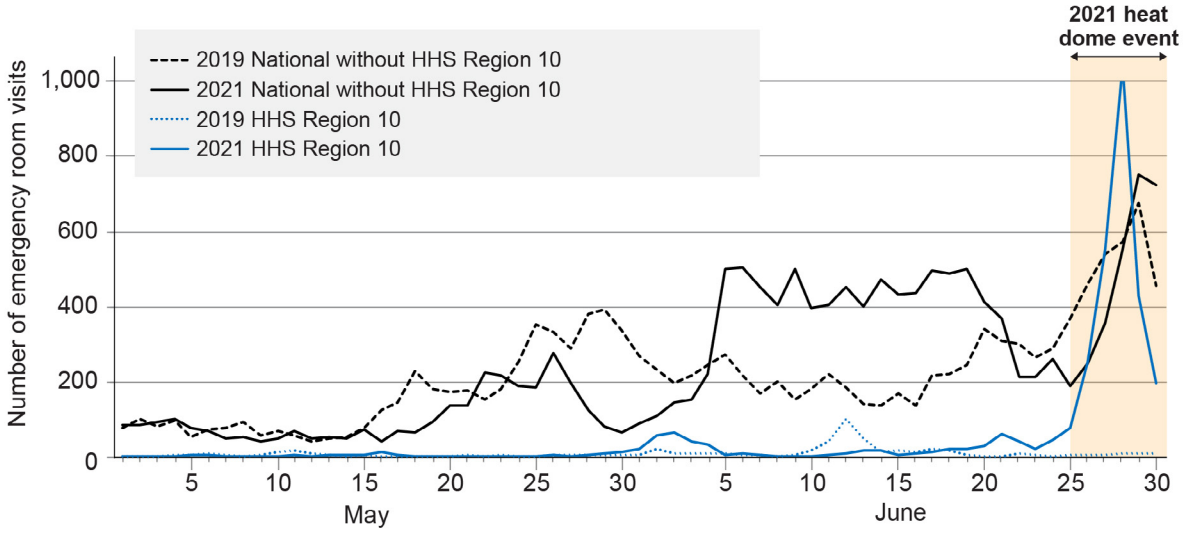
The Northwest's climate has historically been temperate and relatively mild, but shifting weather patterns associated with climate change are adversely affecting physical, mental, and community health (*very high confidence*). The incidence of illnesses and death during extreme heat events and wildfire smoke days is increasing, and climate change is stressing health systems (*high confidence*). Climate-related health risks disproportionately affect certain individuals and groups (*very high confidence*). Climate resilience efforts can be leveraged to improve health, especially among the most vulnerable populations (*high confidence*).

Multiple public health challenges have been associated with climate change. Those whose livelihoods are dependent on the weather—like outdoor day laborers and wildland firefighters—and people with preexisting health conditions and limited coping capacities face some of the gravest challenges (KM 15.1). COVID-19 has overextended the public health sector since 2020 and strained traditional approaches to reducing public health impacts from climate-induced disasters (such as cooling or warming shelters), because convening groups in large areas has been prohibited or limited (Focus on COVID-19 and Climate Change).

### *Physical Health Impacts of Climate Change*

Climate change amplifies health risks, especially for those with underlying health conditions, and leads to physical health impacts such as premature mortality from heatwaves, compromised respiratory health due to wildfire smoke, infectious and vector-borne diseases, exposure to mold and environmental health hazards, diseases in some foods and natural resources such as shellfish toxins (KMs 27.2, 27.6), and exposure to toxicants (KM 15.1). Heatwaves and extreme heat, which are increasing in frequency and intensity, kill more people annually than any other natural hazard.[328,329] Increasing frequency of wildfires will increase the number of poor air quality days.[75] Together, heat and wildfire smoke have caused thousands of deaths in the Northwest since 2018. The greatest number of deaths occurred in summer 2021 (Figure 27.8)[330] when almost a thousand people perished during an extraordinary heatwave that was partially attributed to climate change.[331,332] Although it is unknown whether events such as the 2021 heat dome are an anomaly or will become increasingly frequent in the Northwest,[333] future heat-related morbidity and mortality across the Northwest are expected to increase across all scenarios.[69,334] Many of these deaths were preventable and happened because communities were maladapted to the level of heat, which disproportionately affected women, people of color, and people with chronic illnesses and placed additional strain on the Northwest's healthcare system.[69,330]

## Heat-Related Emergency Room Visits for Health and Human Services (HHS) Region 10

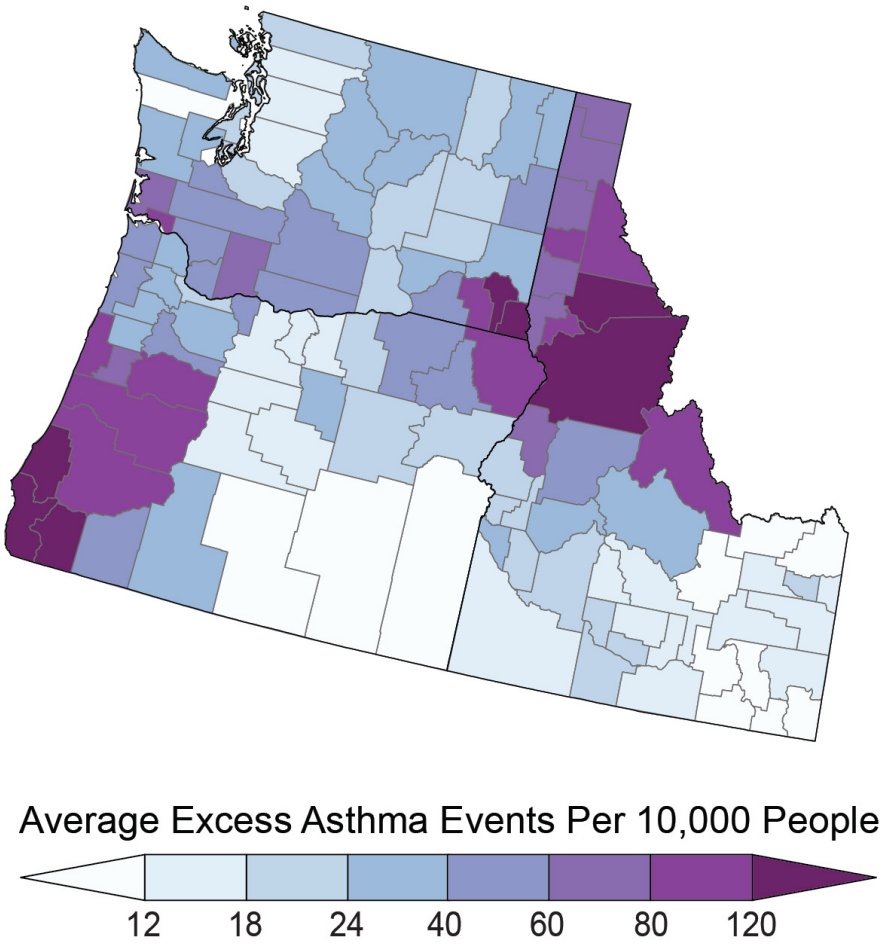



**Heatwaves, such as the heat dome event in the summer of 2021, place strains on healthcare systems.**

**Figure 27.8.** The graph shows the number of heat-related emergency department visits for US Department of Health and Human Services (HHS) Region 10 (which includes Alaska, Oregon, Idaho, and Washington), relative to the rest of the country, from May 1–June 30 in 2019 and 2021. There was a sharp increase in emergency department visits for heat-related illness during the 2021 heat dome event in HHS Region 10, relative to the heat-related emergency department visits for the region in 2019. HHS Region 10 also experienced relatively more heat-related emergency department visits during the 2021 heat dome event compared to the rest of the country over the same time period. Adapted from Schramm et al. 2021.[335]

Wildfire smoke can be severe in the region, particularly in highly populated areas, Idaho, and eastern Washington and Oregon.[321,336] In the western US, smoke events from 2004 through 2009 were associated with a 7.2% increase in respiratory hospital admissions among adults over 65, compared to the previous decade. In Washington, smoke-related mortality increased during the 2020 wildfire season, when the ambient total particulate matter concentration changed from near zero to 100 micrograms per cubic meter ($\mu g/m^3$) over the course of a summer.[322] Increased particulate matter ($PM_{2.5}$) due to wildfire smoke in the West has been associated with a predisposition to COVID-19 and higher COVID-19 case rates and mortality.[337] Future wildfire seasons—and increases in $PM_{2.5}$ associated with those wildfire seasons—is projected to increase excess asthma incidences by the 2050s under a very high scenario (RCP8.5; Figure 27.9); Washington, Oregon, and Idaho are expected to see an increase of 25.7, 41.9, and 29.4 wildfire smoke–related emergency department visits per 10,000 persons, respectively.[336] The anticipated financial burden of healthcare costs associated with wildfire smoke exposure is expected to significantly increase across the Northwest.[336,338,339]

## Projected Asthma Burden per Wildfire Season in 2050




**Excess asthma burden associated with wildfire smoke is expected to disproportionately affect the Northwest.**

**Figure 27.9.** Northern Idaho, coastal Oregon, and southwest Washington are expected to face some of the highest wildfire smoke–related asthma burden in the Northwest. Excess asthma incidences related to wildfire smoke are expected to increase across the Northwest. The figure shows the average expected total number of excess asthma events per 10,000 people per wildfire season by the 2050s under a very high scenario (RCP8.5). Adapted from Stowell et al. 2022[336] [CC BY 4.0].

Additional health-related impacts are associated with heatwaves and wildfire smoke.[340] Lower birth weight and premature birth are attributed to these events,[341,342] although empirical evidence from the Northwest is still emerging. Similarly, evidence of an association between repeated long-term exposure to wildfire smoke and cancer incidence is emerging.[343]

People with access to air-conditioners or air purifiers, along with the financial capacity to operate these systems, will fare better than those whose homes are poorly insulated and allow for a greater concentration of ambient pollutants to enter indoor spaces. Young children and older adults are particularly vulnerable, as are those who live in trailer parks, recreational vehicles, or historically disinvested urban areas. Discriminatory policies such as redlining also contribute to greater exposure to heat and other climate-induced events, such as urban flooding (KM 27.1).

## Mental Health Impacts and Climate Change

Each extreme event has its own set of observed mental health consequences, including some overlapping disorders such as post-traumatic stress, anxiety, depression, and suicide.[344,345] Negative mental health outcomes have been observed before and after a climate-related extreme event.[346] For example, wildfire smoke can limit outdoor activities, reducing individuals' ability to exercise, recreate, and relieve stress, leading to additional mental health consequences (KM 27.6). Mental health consequences of climate change may resolve quickly; however, long-term impacts can be delayed and, in the case of post-traumatic stress, can even affect future generations.[347,348]

Idaho, Oregon, and Washington have a higher prevalence of mental illness relative to the rest of the country.[349] The mental health impacts of climate change will continue to be uneven. Youth concerned about climate change, Tribal communities losing cultural resources at a rapid pace, and houseless individuals who experience increased exposures to climate change have a higher prevalence of climate-related mental illnesses compared to other populations.[345,350,351,352]

## Community Health and Well-Being Impacts

Climate change impacts community health and well-being in many ways. Increased temperatures are associated with an increase in violence and self-harm, including suicide.[344,353] The magnitude and duration of droughts in the Northwest are projected to increase and potentially disrupt agricultural production and exacerbate food insecurity,[354] which can cause psychological distress.[355] Extreme events will continue to disrupt medical care and services, and injury and illness from such events are expected to exceed the capacity of the healthcare system. Strengthening community and social cohesion can improve community health outcomes and increase preparedness for disasters and extreme events.[356,357]

## Tribal Well-Being Impacts

Climate change is disrupting Tribal communities' access to traditional foods, compounding legacy effects of settler colonialism that have led to increased consumption of processed foods, which is associated with higher rates of diabetes, heart disease, and obesity for Tribal communities.[358,359,360] Algal blooms have contaminated shellfish to the point that they cannot be consumed during traditional seasons (KM 27.2). Increasing temperatures have created more favorable conditions for transmission of parasitic and invasive species among food sources such as deer and fish.[361,362] The continued effects of climate change on the phenology of important species and access to cultural resources are expected to disrupt multiple cultural and ceremonial activities, compounding mental, cultural, and physical well-being issues for Tribes.[265,352,363] Impacts to these cultural resources and sites disrupt intergenerational teachings, an important component of Indigenous health and a method to address intergenerational trauma (KM 27.6).[364]

## Climate Action Can Benefit Human Health and Address Inequities

Historically, the intersection of climate change and health has been unclear, leading to insufficient capacity and resources for health agencies to properly respond and prioritize climate change actions.[365] However, because of the health consequences of recent extreme events, public health responses to climate change have become an essential part of climate adaptation, and health resilience frameworks, such as the CDC's Building Resilience Against Climate Effects (BRACE) or Oregon's Climate Equity Blueprint, are becoming more common.[366] Many strategies—such as setting universal climate and health goals and providing adequate resources to communities and populations to reach these goals—offer promise for avoiding negative public health outcomes due to climate change and can advance regional resilience (KM 27.1).[367] For example, investments to increase electric vehicle adoption and active transportation (e.g., walking, biking) are expected to lead to greenhouse gas emissions reductions, improvements in air quality, and reductions in fatal traffic accidents.[368] Investments in cooling options—such as shade coverage from trees, cross-ven-

tilation in apartment units, and air-conditioning capacity—can support communities, particularly formerly redlined communities, in adapting to extreme heat events (KM 27.1).[369]

## Key Message 27.6

## Climate Change Affects Heritage and Sense of Place

Climate change has disrupted sense of place in the Northwest, affecting noneconomic values such as proximity and access to nature and residents' feelings of security and stability (*high confidence*). Place-based communities, including Tribes, face additional challenges from climate change because of cultural and economic relationships with their locale (*very high confidence*). Leveraging local or Indigenous Knowledge and value systems can spur climate action to ensure that local heritage and sense of place persist for future generations (*medium confidence*).

The heritage of the Northwest is intertwined with the diversity of landscapes, economies, and quality of life (Figure 27.10). Climate change affects all these core characteristics of the Northwest, with impacts on the quality of life and sense of place—the attachment or relationship that people feel to their locations and environment—for all communities and the ability to share the familiar parts of where one lives with others and across generations.[370] While there are differences among cultures' relationships, there are deep commonalities. Supporting the continued emotional and cultural well-being of residents across the region will require a mutual appreciation from multiple perspectives across diverse communities.

### *Sense of Stability and Security*

Climate change can negatively affect peoples' sense of security and stability due to disruptions to supply chains and food systems, which underpin economies and communities (KM 18.2; Focus on Risks to Supply Chains).[371,372] For example, a forest products industry requires regular inputs of timber and cannot thrive on supplies that increasingly come in pulses or waves due to drought, wildfires, and insect infestations.[373] Climate change impacts to natural resource economies will affect residents' financial security and livelihoods (KM 27.3) and will have cascading impacts across regional to international economic systems (KM 19.2).

## Heritage, Sense of Place, and Amenities at Risk

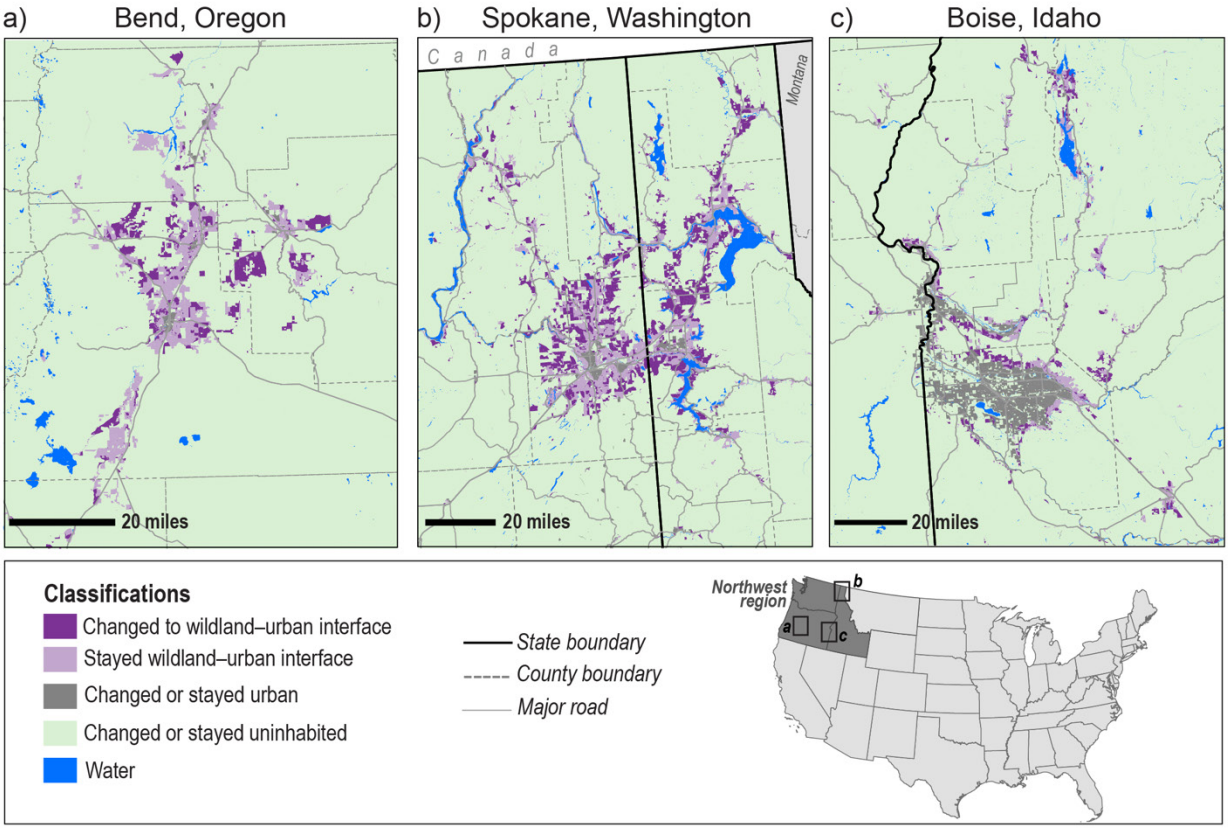
**The heritage of the Northwest is intertwined with the diversity of landscapes, economies, and quality of life.**

**Figure 27.10.** These photos illustrate different heritages, cultural traditions, and amenities at risk from climate change. (**top left**) Coastal change is threatening beaches and shellfish habitat for the Swinomish Tribe, threatening cultural activities like the Swinomish Clam Bake. (**top right**) Fire retardant drops protect vulnerable homes in the wildland–urban interface. (**center left**) Culturally important foods, such as camas, will be affected by climate change. (**center right**) Climate change is affecting salmon, potentially affecting the ability of some Tribes to roast and smoke salmon. (**bottom left**) Wildfire smoke days are increasing, affecting school recreation opportunities. (**bottom right**) Warmer winters, such as the winter of 2015, will lead to less winter snow, affecting ski resorts such as Mount Baker Ski Resort, Washington, which had no snow on February 15, 2015, during the height of ski season. Photo credits: (top left) ©Richard A. Walker; (top right) National Interagency Fire Center; (center left and bottom left) ©Charles Luce; (center right) ©Samantha Chisholm Hatfield; (bottom right) ©Duncan Howat.

Many in the Northwest have moved from city centers to an expanding wildland–urban interface (WUI) (Figure 27.11),[102,103,104] increasing community exposure to wildfires and floods.[374] Homes dependent on shallow wells are at risk from more frequent and intense drought conditions (KM 27.4).[375] Increases in the frequency

of algal blooms or outbreaks of forest diseases and pests reduce the value of homes with water frontage or surrounded by forest (KM 19.3).[376,377,378] The decline of home values, aggregated across communities, can lead to local economic and community instability by reducing the desire or ability to rebuild after fires and floods.[379,380] Although insured households may be able to rebuild, climate risks can increase insurance costs and decrease insurance availability, affecting which residents and businesses thrive in the future.[381]

### Growth in Wildland–Urban Interface (1990–2020)




**The growth of homes in the wildland–urban interface puts an increasing number of people at risk of wildfire and flooding.**

**Figure 27.11.** The maps show growth in the wildland–urban interface (WUI; dark purple) areas, which are associated with increased wildfire and flooding risks, between 1990 and 2020 near Bend, Oregon (**a**); Spokane, Washington (**b**); and Boise, Idaho (**c**). Bend and Spokane have experienced fast rates of development and population growth that have led to new areas being developed as WUI. Figure credit: USDA Forest Service, NOAA NCEI, and CISESS NC.

## *Environmental Amenities and Sense of Place*

Northwest residents value the region for its environmental amenities like good air and water quality and proximity to recreational opportunities.[263,382] Climate change has already started and will continue to disrupt many kinds of outdoor recreational activities.[79,383] Multiple recreational seasons have simultaneously shortened and shifted. Skiing and snowmobiling seasons have started later and become shorter over much of the region, especially in the Cascades,[13,384] affecting winter recreation businesses (KM 27.3). Loss of spring snowmelt will shift opportunities for rafting, kayaking, and canoeing into rainy winter months, when rapidly fluctuating flow conditions are less safe. Water-based recreation demand is expected to increase in spring

and summer months; however, reduced water quality and harmful algal blooms are expected to restrict these recreation opportunities.[79]

Many previously forested trails and camping areas have already lost forest cover due to wildfires and drought.[385] As the frequency of disturbances increases, so will the number of dead and downed trees,[386] closing roads, trails, and campgrounds and potentially causing injuries or death for recreationists.[387] Greater flooding risk in winter months will pose risks to recreational facilities and users.[388] More frequent smoke and extreme heat events will increase risks to outdoor summer recreationists, especially for high-exertion activities.[389] State health agencies, such as the Idaho Department of Health and Welfare, have developed recreation guidelines for K–12 and adult fitness activities and sports in response to increasing wildfire smoke days and decreased air quality.[390]

Climate change will also affect recreational and subsistence hunting, gathering, and fishing activities. Although some game species may benefit from increased shrub cover and reduced winter mortality, increasing populations can lead to other challenges, affecting managed resources and increasing pathogen spread.[391,392] Algal blooms and increased toxin levels will lead to shellfish harvest closures, sometimes lasting entire seasons. While these impacts will affect recreational hunters and fishers, impacts will be greater for households and communities that are nutritionally dependent on these resources, such as Tribal communities and households reliant on subsistence diets.[393]

Amenity migration, or movement of people to areas with higher environmental quality or increased access to amenities, will be affected by climate change in various ways.[394,395] For example, people moving to the WUI to be closer to environmental amenities will experience increased risks of wildfires and, in some cases, landslides (Figure 27.11). Additionally, there are compounding challenges for communities that are receiving an influx of amenity migrants, especially rural and low-income communities where established residents provide the labor force but may become priced out by increasing costs of housing and other necessities.[396,397] Interacting stresses between socioeconomic and development impacts associated with migration and climate change will affect communities in high-amenity areas in the Northwest, such as ski communities in the Cascade Range or island communities in the San Juan Islands.[398]

## *Tribal Cultures and Connection to the Land*

Climate change has affected Tribal harvesting, hunting, and ceremonial practices.[399] Climate change will impact Pacific salmon (KM 27.2) and other cultural resources such as Pacific lamprey, deer, elk, bear, berries, eel, flounder, sturgeon, shellfish, and seaweeds.[400] Plant die-offs and range shifts can disrupt and impede Tribal access to traditional foods, thereby affecting Tribes' and Indigenous Peoples' sense of place and connections (KM 27.5).[363] Extreme weather events and extreme heat and cold can prevent Tribal members, especially elders, from participating in Tribal ceremonies. Access to ceremonial sites can also be disrupted or damaged by flooding, landslides, and wildfires, exacerbating degradation associated with other land-use decisions (KM 27.1).

Indigenous Knowledges can be utilized to increase resilience to climate change for Tribes.[251] Tribal landscape management is one method for maintaining connections to landscapes and preserving ceremonial sites, medicinal plants, and gravesite locations for future generations.[401,402,403] However, federal, state, and local jurisdictions have prevented some Tribes from utilizing Indigenous management techniques such as prescribed burning, which can remove underbrush to reduce fire risk and establish wildlife corridors (KM 27.2), thereby limiting Tribes' ability to exercise their sovereignty and to maintain a sense of place for future generations.[404,405,406,407,408] Western adaptation options of replacement, fortification, or relocation (KM 27.4) may not be possible or appropriate, as some sites (e.g., gravesites and ceremonial sites) do not have one-to-one exchange equivalents. Despite these limitations, federal–Tribal partnerships can increase landscape resilience to future climate change risks.[409,410]

## *Maintaining a Sense of Place and Heritage for the Northwest*

Climate change poses an existential threat to the ability of Northwest communities to maintain their sense of place and heritage for future generations. Many cultures rely on nature-based experiences to transfer knowledge and form cultural identity. For example, the Swinomish Tribe holds cultural clam bakes, where community elders transfer Traditional Knowledges about the natural world that are vital to maintain their cultural well-being and heritage.[399] However, recent shoreline changes and projected beach loss threaten access to these culturally important shellfish harvest areas, reducing opportunities to hold cultural clam bakes.[411]

Communities across the Northwest pride themselves on their environmental values and actions, such as promoting conservation or voluntarily employing sustainable practices. Leveraging these community values can lead to innovative climate adaptation and mitigation policies at the local level,[412,413] furthering regional climate mitigation and adaptation goals (KM 27.4) to ensure that the heritage and the communities of the Northwest persist for future generations.

# Traceable Accounts

## *Process Description*

The Northwest chapter focuses on advances in regional climate science and understanding of the social and economic impacts of climate change. Therefore, the author team reflects the breadth and depth of scholarship and experiences about climate science, impacts, and responses. The author team was recruited from a list of nominated authors, regional experts from past assessments and conferences, and recommendations from authors or author candidates. The author team includes: 1) a diversity of expertise in the areas of physical climate science, social sciences, economics, public health, ecosystem services, adaptation, and mitigation; 2) a diversity of geographies and institutions that represent each state in the Northwest; 3) a range of experiences and career stages that includes university researchers, practitioners, and state government employees; and 4) a diversity across multiple demographic characteristics, including gender, race, and ethnicity.

Initial Key Message themes were developed via consensus, and these Key Messages were confirmed at the Northwest's regional engagement workshop on February 1, 2022. Specific content within the Key Messages was further refined based on comments from the regional engagement workshop and public comments on the Zero Order Draft. Authors were assigned to Key Message–specific teams based on their expertise and were charged with developing the text, citations, Traceable Accounts, and Key Messages. Key Message narratives were developed to ensure that content built off prior National Climate Assessments (NCAs) and was not repetitive of previous NCAs (Table 27.2). Author meetings were generally held biweekly throughout development of the Fifth National Climate Assessment (NCA5) for discussions and deliberations and to ensure that deadlines were met. Additionally, the smaller Key Message teams met frequently to refine their Key Messages, text, figures, and Traceable Accounts.

**Table 27.2. How NCA5 Northwest Chapter Built on Prior NCAs**

| NCA5 Key Message | How NCA5 Built on NCA3[5] and NCA4[4] |
|---|---|
| 27.1 Frontline Communities | Since NCA4, much more research has been published on the distributional burden of climate change on various communities across the Northwest. NCA5 expands on the literature base to focus on the different dimensions of how climate change inequitably impacts various groups. Additionally, NCA5 focuses on some of the emerging information on how different frontline groups are advancing climate action within their communities and states. |
| 27.2 Ecosystem Changes | More research has been published since both NCA3 and NCA4 on the ecological impacts of climate change. NCA5 builds on this work by focusing on ecological responses across the Northwest to extreme events and the interaction between climate change and human activity (e.g., land use). Additionally, NCA5 builds on how different types of adaptation responses, such as restoration, can build ecological resilience. |
| 27.3 Economics and Well-Being | Since NCA3 and NCA4, there has been more scholarship on the economic impacts of climate change. NCA5 dives deeper into some economic impacts previously discussed, including impacts to the natural resource economy. NCA5 also provides a synthesis of new research on the recreational impacts of climate change and economic opportunities in a low-carbon future. |
| 27.4 Infrastructure and Resilience | NCA5 builds on NCA3 and NCA4 by focusing on different types of infrastructure systems and their responses to climate change. NCA5 also highlights the trade-offs of climate action across systems, such as the trade-off between transportation electrification and energy resilience. Additionally, NCA5 focuses on how infrastructure systems and the built environment are the largest contributors of greenhouse gas emissions and provides a narrative on climate mitigation and decarbonization in the region. |
| 27.5 Health Inequities | Since NCA4, more extreme events, such as large wildfires, more wildfire smoke days, and extreme heatwaves, have led to health consequences. NCA5 builds on NCA4, which delved into a variety of impacts, by focusing primarily on heat and smoke impacts to public health. Additionally, NCA5 adds emerging research on the mental and community health impacts of climate change. |
| 27.6 Heritage and Sense of Place | Since NCA4, there has been more research that establishes how regional sense of place is changing due to climate change. NCA5 provides more in-depth coverage on many of the topics covered in NCA4, such as sense of security from extreme events, how different amenities are changing, and how different iconic parts of the Northwest are being affected. Additionally, NCA5 provides additional discussion of climate-related migration and how that affects a community's identity and sense of place. |

## Key Message 27.1

## Frontline Communities Are Overburdened, and Prioritizing Social Equity Advances Regional Resilience

### Description of Evidence Base

Recent studies and reports have built on decades of research that have provided strong evidence that the prevalence of people of color in a community continues to be the most significant predictor for where environmental hazards are sited throughout the Northwest, due to racialized and racist policies.[59,60,62,63,64,65,66,97] A wealth of evidence, including peer-reviewed research, gray literature, and government reports and resources, links racial and socioeconomic demographics across the Northwest with disproportionate exposure and vulnerability of frontline communities to a variety of climate

hazards and extreme events, including wildfire, wildfire smoke and impaired air quality, extreme heat, and flooding.[59,61,62,67,68,70,71,74,75,76,77,89,92,93,95,414]

Additionally, NCA5 listening sessions and community-led research provided evidence on the lived experiences of frontline communities with climate impacts and how these communities are implementing community-informed climate resilience priorities. The literature supports the diversity of approaches that frontline communities are utilizing to increase their resilience to climate change, including for urban communities of color,[59,97] rural and natural resource–dependent communities,[79,80,81] and Tribal and Indigenous communities.[93,265] Peer-reviewed literature and gray literature document that while frontline communities are inherently resilient to both climate change and other forms of oppression, policies and other structural barriers continue to prevent frontline communities from enacting community-led adaptation strategies.[78,90,91,92,93]

## Major Uncertainties and Research Gaps

While the priorities and needs of frontline communities are increasingly being considered in state and local government policies, plans, and budgets in the Northwest, such efforts are in early stages of implementation. While these efforts are resulting in some benefits to frontline communities in the near term, long-term outcomes are yet to be seen. Advancing climate justice and social equity in the region is dependent on institutions' ability to transform and meet the needs of frontline communities.

While community-led research and plans provide documentation of frontline communities' priorities, it is critical to note that these sources probably do not represent the full range of perspectives, values, and experiences of the diverse communities in the Northwest. Assessment authors understand that communities are not monoliths and that many adaptation and resilience strategies are culturally, temporally, and geographically specific; therefore, the information in this assessment cannot be used to make blanket statements about all communities experiencing environmental and climate injustices in the region.

## Description of Confidence and Likelihood

Based on the breadth of available research and literature, authors concluded that there is *very high confidence* that frontline communities are experiencing disproportionately high exposure to climate-related hazards, although there is variation across the types of frontline communities.

Additionally, because of the wealth of community-led documentation, government reports, and preliminary peer-reviewed research, authors concluded that there is *high confidence* that frontline communities generally have fewer resources to adapt and respond to climate change but are leading efforts to increase resilience to climate change and extreme events.

While there is a growing body of evidence suggesting that the priorities, values, and needs of frontline communities are increasingly being considered in state and local policies and plans, these efforts are still in early stages of implementation and long-term outcomes remain to be seen. In addition, existing efforts are not yet sufficient to meet the scale and speed of justice-centered climate action required to secure a safe and livable future for frontline communities. Therefore, authors of this Key Message have *medium confidence* that the extent of these efforts will deliver long-term resilience benefits and climate justice to the region.

## Key Message 27.2

# Ecosystems Are Transitioning in Response to Extreme Events and Human Activity

### Description of Evidence Base

Strong evidence supports the projection that ecosystems will change as climate changes. Numerous assessments project extensive changes in species distributions as climate changes. Additionally, extreme events (e.g., droughts, floods, and heatwaves), which are becoming more frequent and intense, may be equally relevant to the physical condition and population dynamics of species,[107,109] especially those with short generation times.[110] Multiple peer-reviewed publications and government reports document the extensive impacts of extreme events on Northwest ecosystems, especially in the past two decades. Given projections of future climate, it is expected that wildfire will continue to affect forest systems,[113,114,115,116,117,118,119,120,121,123] changes in hydrology and temperature will affect aquatic ecosystems,[128,129,130,131,132,133,134,138,139] and ocean acidification and marine heatwaves will affect coastal and marine systems.[42,48,54,145,146,147,148,149,150,151,152,154,155,159,415]

In addition, robust peer-reviewed evidence documents how these ecosystem-level changes will have myriad effects on native species, including game species,[391,392] trees,[232,234,237,238,244] marine taxa,[148,149,150] and the region's iconic salmonids[48,159,160,161,162,163,164,165,415]

Extensive evidence within the peer-reviewed literature also demonstrates the widespread impact of human land uses on the extent to which species can adapt to environmental change, including climate change.[104,118,119,120,121,122,144] For example, fine-grained variation in land cover, including land cover types associated with human activities, affects the resilience of species or ecological processes to climate variability and change[189] and the extent to which land uses function as stressors. Historical and recent fragmentation of a species' habitat and barriers to movement affect its capacity to adapt to both human-caused and natural forms of environmental change.[129,130,144,186,187]

There is extensive evidence that conservation of genetic diversity and ecological protection and restoration can benefit ecosystem processes and increase species' adaptive capacity.[120,121,122,192,193,194,195,196] For example, restoration via removal of impassable dams and structures across the Northwest has restored some natural ecological and hydrological processes that allow anadromous fishes to access historical habitat.[194,197,198,199,200] However, evidence of the effectiveness of other types of ecological management, such as vegetation removal to mitigate wildfire risk and market-based ecosystem management tools, is limited, especially in the long term.[204,205,206,208,209]

### Major Uncertainties and Research Gaps

Relations between climate and population dynamics of most species are complex, so there is uncertainty in projections even for well-studied species. Moreover, distributions, abundances, or other species-level metrics more closely reflect interactions among climate variables, and interactions among species, rather than single climate variables.[111,112]

Evolutionary responses to climate are also complex.[212,213] The likelihood of adaptation depends in part on the amount of genetic variation in a population or species, which is often related to the number of individuals and their relatedness.[188] The feasibility of quantifying abundance, relatedness, and genetic variation differs among populations and species, and these measures have not been estimated for a majority of populations and species. Furthermore, empirical estimates of opposing selection pressures in different environments are difficult to obtain. Similarly, phenotypic plasticity, its heritability, and potential response to selection have not been estimated in most taxa. Accordingly, the adaptive capacity of most taxa is highly uncertain.

Also, data on which biological and physical attributes affect viability most strongly are not available for most species.

The extent to which restoration efforts can increase genetic variation and ecosystem function and productivity is uncertain, especially given the extensive anthropogenic modification of ecosystem structure, composition, and function. Because ecosystems rarely can be restored to a historical state, restoration actions tend to focus on increasing ecosystems' capacity to support diverse and valued functions and services and enhanced genetic and species variation. Information needs include improved understanding of habitat quality, stress tolerance, and adaptation capacity of diverse species. There are substantial gaps in understanding of the complex interactions within and among species, communities, and biogeochemical processes, all of which are being modified by climate change and land use.

### Description of Confidence and Likelihood

The enormous body of evidence on ecological sensitivity to climate yields *very high confidence* in projections of change, despite uncertainty in how individual and interacting ecological components will respond. Similarly, although adaptive capacity is difficult to quantify, there is *very high confidence* that such capacity has been reduced by decreases in abundance and genetic diversity of many native species. There is *very high confidence* that human activities and land uses interact with ecological responses to climate change, and in many cases exacerbate these effects.

Climate change impacts could be ameliorated by changes in human actions. However, restoration to previous ecological states often is unlikely. For example, certain non-native invasive species are unlikely to be eradicated, and land modifications rarely can be completely reversed. Furthermore, climate change will modify some species and ecosystem characteristics regardless of human actions. Although the scientific community has medium to low confidence that ecosystem restoration efforts can increase genetic variation in many native species, there is high to medium confidence that reconnecting and improving the quality of species' habitats can increase the feasibility of species persistence. The likelihood of ecological recovery is location- and context-specific and depends on factors including the severity of ecological stressors; the location, timing, design, and scope of restoration actions; and the potential to restore abiotic and biotic processes, land cover, and flows of energy and genes. Thus, the authors have *medium confidence* that human-led adaptation efforts can reduce exposure to climate-related hazards.

## Key Message 27.3

## Impacts to Regional Economies Have Cascading Effects on Livelihoods and Well-Being

### Description of Evidence Base

Over the past several decades, multiple peer-reviewed studies have established how climate change affects diverse annual and perennial cropping systems,[216,217,218,219,220,221,222,223] fishery systems,[225,247,248,249,250,253] forestry systems,[233,234,236,237,242,244] and the tourism industry.[16,79,256,257,258,261]

Despite these varying climate impacts, there is emerging science, including peer-reviewed sciences, that indicates that the Northwest continues to maintain economic resilience to climate change due to the region's inherent diversification. For example, federal crop insurance for the Northwest shows multiple weather- and climate-related causes of crop loss (e.g., drought, heat, freeze, frost, excess moisture), demonstrating the diversity of risks agricultural producers experience.[230] However, new and emerging opportuni-

ties in these important economic sectors are also beginning to be noted.[82,83,87,231,243,244,245] The effectiveness and extent of these new adaptation and mitigation opportunities is still unclear.

Emerging case studies, gray literature, and frameworks, such as the just transition framework, are being implemented across the Northwest to transition to a low-carbon economy.[97,246,303,416,417] There are frameworks and evidence that associate economic resilience with prioritizing worker protections and marginalized labor populations.[270,272] However, such publications in the Northwest region are still relatively new and limited in extent.

### Major Uncertainties and Research Gaps

Recent events such as the 2021 heat dome have highlighted the significant impacts of extreme weather. Regional industries are investing in research that can increase understanding of risk factors associated with extreme weather and assess whether the risks are high enough to warrant additional infrastructure investments and management alternatives to limit damage. Much of the existing literature on climate change impacts on the region is based on limited climate ensembles rather than large ensembles, which are key to understanding extreme weather probabilities and impacts. New efforts addressing this gap are starting to be initiated, especially those addressing the regional agricultural industry.

The potential for new adaptation and mitigation opportunities is still unclear. Additional region-specific information is necessary to obtain a better picture of the potential. The region is still in its early phases of implementing low-carbon economy transition plans and strategies. There are still many gaps associated with the efficacy of implementing these plans. Evaluation of the recently launched efforts should provide valuable information for future streamlining of these efforts.

### Description of Confidence and Likelihood

Because of the wealth of peer-reviewed research published across multiple decades, we have *very high confidence* that climate change is affecting—oftentimes in negative ways—natural resource– and outdoor-dependent economies, although the ways they are affected will be variable depending on the location and industry or commodity. Based on robust peer-reviewed literature and a growing number of publications specific to the Northwest, there is *high confidence* that climate change effects on these industries will have cascading impacts on the livelihoods of resource-dependent communities. Because of an emerging evidence base in the peer-reviewed literature—and a nascent evidence base specific to the Northwest region—the authors have *medium confidence* that the region's natural resource industries are effectively responding to climate change and that a transition to a low-carbon economy can impart economic resilience, especially for those disproportionately impacted, such as workers in fossil fuel–dependent industries and outdoor laborers.

## Key Message 27.4

## Infrastructure Systems Are Stressed by Climate Change but Can Enable Mitigation and Adaptation

### Description of Evidence Base

There is considerable evidence that climate change and extreme events have negatively affected built infrastructure, especially older infrastructure, in the Northwest.[100,142,273,278,279,291,307,308,311,318,323] Evidence varies among sectors, and multiple studies document effects of drought on water infrastructure and supply,[277] effects of wildfires on virtually all types of infrastructure,[142,277,418] and effects of extreme precipitation and flooding on water and transportation infrastructure.[29,281,282,283,323]

Multiple studies highlight the interdependencies of systems.[274,275,276,291,294,310,314,315,316] Within the Northwest, infrastructure system dependencies can spark conflicts about trade-offs among uses and between adaptation to and mitigation of climate change. These trade-offs have been documented in peer-reviewed publications and government reports and plans.[293,295,296,314,315,316,419] Furthermore, some studies suggest that climate adaptation and mitigation actions across infrastructure systems can lead to cascading consequences in other sectors, such as public health, water conservation, and land use (Focus on Western Wildfires).[277,278]

Despite these conflicts and trade-offs, emerging case studies document approaches to manage trade-offs in use of water, transportation, and electricity infrastructure. There are examples of new technology and data products to support adaptation[285,286,300,304,305,306] and case studies of collaborative efforts to address these complex systems and their responses to climate change.[105,303,418]

### Major Uncertainties and Research Gaps

Trade-offs among uses of infrastructure and efforts to increase infrastructure resilience create substantial uncertainties in the social and environmental effects of those actions. For example, electrification of mass transit and vehicles can reduce emissions of greenhouse gases but strain energy supplies, affecting adoption of electric vehicles across communities. Similarly, provision of air-conditioning and air filtration, especially in regions where they are currently rare, can alleviate the public health consequences of extreme heat but strain energy supplies. Potential consequences of decreasing wildfire exposure may come at the expense of those medically dependent on electricity.

### Description of Confidence and Likelihood

The available research, peer-reviewed literature, and case studies indicate that there is *very high confidence* that climate change, climate hazards, and climate-related extreme events have stressed the Northwest's built infrastructure, and that there is *very high confidence* that climate change will continue to stress these systems. Additionally, there is broad agreement that these infrastructure systems are complex and interrelated and, therefore, that climate-related impacts or responses to extreme events will present trade-offs and lead to conflicts over use. Within the Northwest, documentation of these conflicts and trade-offs varies among sectors and locations. Nevertheless, the literature continues to highlight trade-offs among systems. Therefore, there is *very high confidence* that climate-related disruptions and efforts to adapt to and mitigate the effects of climate change on a given infrastructure system may stress other infrastructure systems. Multiple case studies highlighted how practitioners are managing these conflicts and trade-offs via collaborative planning, engineering, and design. Given the breadth of case studies across sectors, there is *high confidence* that cross-sectoral and multisystem planning will increase the resilience of built infrastructure systems to future climate change.

## Key Message 27.5

## Climate Change Amplifies Health Inequities

### Description of Evidence Base

An extensive peer-reviewed literature base documents the physical and mental health impacts of extreme events and climate change,[69,75,321,322,330,334,335,336,337,340,341,345] and a smaller but growing evidence base documents the community health impacts of climate change.[344,353,355] The Northwest has experienced more extreme heat events, wildfires, and wildfire smoke days in the past decade, and research has documented mortality and morbidity directly associated with these hazards and impacts.[69,328,329,330,334] The evidence connecting extreme heat, for example, to poor mental health outcomes such as anxiety, psychological fatigue, and suicide is still emerging, although researchers and clinicians are developing promising methodologies and approaches to address climate-related mental health needs.[345]

Multiple lines of evidence document the inequitable distribution of climate-related health risks among Northwest communities.[265,322,337,345,350,351,352,358,359,360,363,364] There are some gaps specific to the Northwest region on climate change impacts to community health (e.g., domestic violence). However, both national and international peer-reviewed articles document these associations. Multiple case studies and gray literature and an emerging peer-reviewed literature base document how health professionals and communities are responding to increasing public and community health challenges induced or exacerbated by climate change.[356,357,364,367]

### Major Uncertainties and Research Gaps

Reports and published studies have focused on community impacts following extreme events, or other traumatic events felt at the community level, that may reduce social cohesion. More research is needed to better understand the regional extent of mental health challenges from climate change and to inform protocols to better prepare health professionals for climate-related community health impacts. There are also opportunities to decolonize public health methods and improve the integration of local and Indigenous knowledge systems and methodologies to better inform public health research.

There is still uncertainty about the extent that climate change will place additional stress on healthcare services in the Northwest. Preliminary research based on previous extreme weather events highlighted medication and medical equipment supply chain challenges, yet the demand for healthcare is expected to increase due to extreme events. However, compounding stresses that lead to shortage of healthcare workers, other public health challenges (e.g., COVID-19), and acute climate-related extreme events are beginning to illuminate potential gaps in the healthcare system.

There is still uncertainty in associating community health impacts, such as domestic violence, with climate change and its subsequent impacts on the healthcare system.

### Description of Confidence and Likelihood

Given the breadth of literature documenting climate change impacts on physical, mental, and community health, the authors have *very high confidence* that climate change is adversely affecting public and community health outcomes in the Northwest. The authors have *high confidence* that mortality and illnesses related to extreme heat events and poor air quality is increasing and further stressing the public health sector. This confidence assignment is based on research that illuminates the association between morbidity and mortality during and after extreme heat events, such as the 2021 heat dome, and the increasing number of wildfire smoke days across the region. The authors also have *very high confidence* that climate change and extreme events worsen existing health disparities, unequally distributing the health burden on groups such as older adults, communities of color, Tribal communities, and low-income communities. On the basis of emerging research and case studies, the authors have *high confidence* that climate adaptation and mitigation efforts can lead to health co-benefits.

## Key Message 27.6

## Climate Change Affects Heritage and Sense of Place

### Description of Evidence Base

In the Northwest, a growing evidence base of scientific literature, gray literature, and community knowledges continues to elucidate the interactions between climate change and the regional amenities and lifestyles that make the Northwest an attractive place to live, work, and visit. For example, multiple peer-reviewed publications document the ways in which climate impacts have disrupted key industries

that are critical to supply chains and economic and community stability[249,371,372,373] and local infrastructure (KM 27.4).[375] Additionally, multiple peer-reviewed publications document the interactions between climate change and land use, such as growth of the wildland–urban interface[102,103,104] and the increasing community exposure to climate-related events such as wildfires and flooding.[103,374,381] Multiple publications document these cumulative risks to safety, amenity access, and sense of place across the Northwest.[376,377,378,379,380,388]

The literature has documented how places with more or higher-quality environmental amenities (e.g., recreation, proximity to outdoors, good air and water quality, less traffic congestion) drives migration to more rural and exurban areas.[263,382] A wealth of gray literature and some peer-reviewed research document how climate change affects amenities, including recreation across all seasons[79,384] and environmental quality.[390] There are multiple peer-reviewed publications that document how impacts to these amenities can lead to regional emigration, migration, and displacement, especially as a result of climate-related extremes.[394,395,396,397,398]

There are multiple lines of research that detail climate-related impacts to place-based communities. For example, climate change will affect Tribes' cultural and subsistence resources,[92,251,265,363,364,399,400] which can have adverse impacts on Tribal sense of place and Tribal health and well-being (KM 27.5).[93,95,363,393,401] Other communities that have generational ties to specific rural or exurban areas—such as industry-specific workers and communities of color—will experience indirect and cascading amenity impacts from climate change that can drive migration either from or into specific regions.[394,396,398]

There are multiple examples of how leveraging community knowledges can result in successful adaptation outcomes; however, the bulk of this research is specific to Tribal communities.[251,399,402,403,404,408,409,411] There is emerging research that documents how other types of local knowledge and community values can drive climate action.[412,413]

## Major Uncertainties and Research Gaps

Generally, the social science research within the Northwest is still developing and strengthening understanding of the connections between climate change and regional sense of place and heritage. Therefore, there are still many uncertainties and research gaps. This includes understanding social and economic responses to extreme events or repeated exposures to climate hazards, how these responses drive intra-regional migration, and how amenity migration can lead to cascading effects of displacement of other place-based communities (e.g., communities that strongly identify with specific industries, such as timber or fishing). There is also uncertainty in motivators for climate action by institutions. While some research is available on the social and political dimensions of climate action, including many case studies, the evidence base is nascent.

## Description of Confidence and Likelihood

Research on climate change impacts to regional amenities, heritage, and sense of place varies by place, amenity, culture, and place. However, a common theme across the evidence base is that climate change is disrupting these regional values and cultures. Accordingly, the authors have *high confidence* that climate change is affecting regional amenities, heritage, and sense of place. Additionally, the authors have *very high confidence* that climate change is affecting place-based communities, such as Tribes and natural resource–based communities, given the breadth of regional and national research on these disproportionate impacts. Extensive scholarship highlights how integrating local and Indigenous Knowledges can support community resilience to climate change. However, there is limited research on how local heritage and values, such as environmental or sustainability values, can lead to climate adaptation and mitigation actions. Therefore, the authors have *medium confidence* that regional heritage and values can spur climate action to ensure the persistence of heritages, cultures, and amenities across the Northwest.

# References


1. U.S. Census Bureau, 2021: 2020 Census Apportionment Results. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/tables/2020/dec/2020-apportionment-data.html

2. Kates, R.W., W.R. Travis, and T.J. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (19), 7156–7161. https://doi.org/10.1073/pnas.1115521109

3. Wilson, R.S., A. Herziger, M. Hamilton, and J.S. Brooks, 2020: From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nature Climate Change*, **10** (3), 200–208. https://doi.org/10.1038/s41558-020-0691-6

4. May, K., C. Luce, J. Casola, M. Chang, J. Cuhaciyan, M. Dalton, S. Lowe, G. Morishima, P. Mote, A. Petersen, G. Roesch-McNally, and E. York, 2018: Ch. 24. Northwest. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1036–1100. https://doi.org/10.7930/nca4.2018.ch24

5. Mote, P., A.K. Snover, S. Capalbo, S.D. Eigenbrode, P. Glick, J. Littell, R. Raymondi, and S. Reeder, 2014: Ch. 21. Northwest. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 487–513. https://doi.org/10.7930/j04q7rwx

6. Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner, 2017: Ch. 6. Temperature changes in the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 185–206. https://doi.org/10.7930/j0n29v45

7. Frankson, R., K.E. Kunkel, S.M. Champion, D.R. Easterling, L.E. Stevens, K. Bumbaco, N. Bond, J. Casola, and W. Sweet, 2022: Washington State Climate Summary 2022. NOAA Technical Report NESDIS 150-WA. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. 5 pp. https://statesummaries.ncics.org/chapter/wa/

8. Runkle, J., K.E. Kunkel, R. Frankson, S.M. Champion, L.E. Stevens, and J. Abatzoglou, 2022: Idaho State Climate Summary 2022. NOAA Technical Report NESDIS 150-ID. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD, 4 pp. https://statesummaries.ncics.org/chapter/id/

9. Rogers, M. and G.S. Mauger, 2021: Pacific Northwest Climate Projection Tool. University of Washington, Climate Impacts Group. https://cig.uw.edu/resources/analysis-tools/pacific-northwest-climate-projection-tool/

10. Salathé Jr., E.P., A. Beggs, C. McJunkin, and S. Sandhu, 2023: The relative warming rates of heat events and median days in the Pacific Northwest from observations and a regional climate model. *Journal of Climate*, **36** (8), 2471–2481. https://doi.org/10.1175/jcli-d-22-0313.1

11. Humes, K., R. Walters, J. Ryu, R. Mahler, and C. Woodruff, 2021: Water report. In: *Idaho Climate-Economy Impacts Assessment*. James A. & Louise McClure Center for Public Policy Research, University of Idaho. https://www.uidaho.edu/president/direct-reports/mcclure-center/iceia/water

12. Ikeda, K., R. Rasmussen, C. Liu, A. Newman, F. Chen, M. Barlage, E. Gutmann, J. Dudhia, A. Dai, C. Luce, and K. Musselman, 2021: Snowfall and snowpack in the western U.S. as captured by convection permitting climate simulations: Current climate and pseudo global warming future climate. *Climate Dynamics*, **57** (7), 2191–2215. https://doi.org/10.1007/s00382-021-05805-w

13. Lute, A.C. and C.H. Luce, 2017: Are model transferability and complexity antithetical? Insights from validation of a variable-complexity empirical snow model in space and time. *Water Resources Research*, **53** (11), 8825–8850. https://doi.org/10.1002/2017wr020752

14. Mote, P.W., S. Li, D.P. Lettenmaier, M. Xiao, and R. Engel, 2018: Dramatic declines in snowpack in the western US. *Npj Climate and Atmospheric Science*, **1** (1), 1–6. https://doi.org/10.1038/s41612-018-0012-1

15. Nolin, A.W. and C. Daly, 2006: Mapping "at risk" snow in the Pacific Northwest. *Journal of Hydrometeorology*, **7** (5), 1164–1171. https://doi.org/10.1175/jhm543.1

16. Clifton, C.F., K.T. Day, C.H. Luce, G.E. Grant, M. Safeeq, J.E. Halofsky, and B.P. Staab, 2018: Effects of climate change on hydrology and water resources in the Blue Mountains, Oregon, USA. *Climate Services*, **10**, 9–19. https://doi.org/10.1016/j.cliser.2018.03.001

17. Wagner, A.M., K.E. Bennett, G.E. Liston, C.A. Hiemstra, and D. Cooley, 2021: Multiple indicators of extreme changes in snow-dominated streamflow regimes, Yakima River Basin region, USA. *Water*, **13**, 2608. https://doi.org/10.3390/w13192608

18. Chang, H., I.-W. Jung, M. Steele, and M. Gannett, 2012: Spatial patterns of March and September streamflow trends in Pacific Northwest streams, 1958–2008. *Geographical Analysis*, **44** (3), 177–201. https://doi.org/10.1111/j.1538-4632.2012.00847.x

19. Dalton, M., and E. Fleishman, Ed. 2021: *Fifth Oregon Climate Assessment*. Oregon State University, Oregon Climate Change Research Institute, Corvallis, OR. https://ir.library.oregonstate.edu/concern/technical_reports/pz50h457p

20. Kormos, P.R., C.H. Luce, S.J. Wenger, and W.R. Berghuijs, 2016: Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams. *Water Resources Research*, **52** (7), 4990–5007. https://doi.org/10.1002/2015wr018125

21. Fountain, A.G., C. Gray, B. Glenn, B. Menounos, J. Pflug, and J.L. Riedel, 2022: Glaciers of the Olympic Mountains, Washington—The past and future 100 years. *Journal of Geophysical Research: Earth Surface*, **127** (4), e2022JF006670. https://doi.org/10.1029/2022jf006670

22. Frans, C., E. Istanbulluoglu, D.P. Lettenmaier, A.G. Fountain, and J. Riedel, 2018: Glacier recession and the response of summer streamflow in the Pacific Northwest United States, 1960–2099. *Water Resources Research*, **54** (9), 6202–6225. https://doi.org/10.1029/2017wr021764

23. Lee, S.-Y., A.F. Hamlet, and E.E. Grossman, 2016: Impacts of climate change on regulated streamflow, hydrologic extremes, hydropower production, and sediment discharge in the Skagit River Basin. *Northwest Science*, **90** (1), 23–43. https://doi.org/10.3955/046.090.0104

24. Lancaster, S.T., A.W. Nolin, E.A. Copeland, and G.E. Grant, 2012: Periglacial debris-flow initiation and susceptibility and glacier recession from imagery, airborne LiDAR, and ground-based mapping. *Geosphere*, **8** (2), 417–430. https://doi.org/10.1130/ges00713.1

25. Lorente-Plazas, R., T.P. Mitchell, G. Mauger, and E.P. Salathé, 2018: Local enhancement of extreme precipitation during atmospheric rivers as simulated in a regional climate model. *Journal of Hydrometeorology*, **19** (9), 1429–1446. https://doi.org/10.1175/jhm-d-17-0246.1

26. Gershunov, A., T. Shulgina, R.E.S. Clemesha, K. Guirguis, D.W. Pierce, M.D. Dettinger, D.A. Lavers, D.R. Cayan, S.D. Polade, J. Kalansky, and F.M. Ralph, 2019: Precipitation regime change in western North America: The role of atmospheric rivers. *Scientific Reports*, **9** (1), 9944. https://doi.org/10.1038/s41598-019-46169-w

27. Slinskey, E.A., P.C. Loikith, D.E. Waliser, B. Guan, and A. Martin, 2020: A climatology of atmospheric rivers and associated precipitation for the seven U.S. National Climate Assessment regions. *Journal of Hydrometeorology*, **21** (11), 2439–2456. https://doi.org/10.1175/jhm-d-20-0039.1

28. Xiong, Y. and X. Ren, 2021: Influences of atmospheric rivers on North Pacific winter precipitation: Climatology and dependence on ENSO condition. *Journal of Climate*, **34** (1), 277–292. https://doi.org/10.1175/jcli-d-20-0301.1

29. Corringham, T.W., F.M. Ralph, A. Gershunov, D.R. Cayan, and C.A. Talbot, 2019: Atmospheric rivers drive flood damages in the western United States. *Science Advances*, **5** (12). https://doi.org/10.1126/sciadv.aax4631

30. Hughes, M., D. Swales, J.D. Scott, M. Alexander, K. Mahoney, R.R. McCrary, R. Cifelli, and M. Bukovsky, 2022: Changes in extreme integrated water vapor transport on the U.S. west coast in NA-CORDEX, and relationship to mountain and inland precipitation. *Climate Dynamics*, **59** (3), 973–995. https://doi.org/10.1007/s00382-022-06168-6

31. Payne, A.E., M.-E. Demory, L.R. Leung, A.M. Ramos, C.A. Shields, J.J. Rutz, N. Siler, G. Villarini, A. Hall, and F.M. Ralph, 2020: Responses and impacts of atmospheric rivers to climate change. *Nature Reviews Earth & Environment*, **1** (3), 143–157. https://doi.org/10.1038/s43017-020-0030-5

32. Shields, C.A. and J.T. Kiehl, 2016: Atmospheric river landfall-latitude changes in future climate simulations. *Geophysical Research Letters*, **43** (16), 8775–8782. https://doi.org/10.1002/2016gl070470

33. Rutz, J.J., W.J. Steenburgh, and F.M. Ralph, 2014: Climatological characteristics of atmospheric rivers and their inland penetration over the western United States. *Monthly Weather Review*, **142** (2), 905–921. https://doi.org/10.1175/mwr-d-13-00168.1

34. Espinoza, V., D.E. Waliser, B. Guan, D.A. Lavers, and F.M. Ralph, 2018: Global analysis of climate change projection effects on atmospheric rivers. *Geophysical Research Letters*, **45** (9), 4299–4308. https://doi.org/10.1029/2017gl076968

35. Gao, Y., J. Lu, L.R. Leung, Q. Yang, S. Hagos, and Y. Qian, 2015: Dynamical and thermodynamical modulations on future changes of landfalling atmospheric rivers over western North America. *Geophysical Research Letters*, **42** (17), 7179–7186. https://doi.org/10.1002/2015gl065435

36. Mahoney, K., D. Swales, M.J. Mueller, M. Alexander, M. Hughes, and K. Malloy, 2018: An examination of an inland-penetrating atmospheric river flood event under potential future thermodynamic conditions. *Journal of Climate*, **31** (16), 6281–6297. https://doi.org/10.1175/jcli-d-18-0118.1

37. Warner, M.D. and C.F. Mass, 2017: Changes in the climatology, structure, and seasonality of northeast Pacific atmospheric rivers in CMIP5 climate simulations. *Journal of Hydrometeorology*, **18** (8), 2131–2141. https://doi.org/10.1175/jhm-d-16-0200.1

38. Massoud, E.C., V. Espinoza, B. Guan, and D.E. Waliser, 2019: Global climate model ensemble approaches for future projections of atmospheric rivers. *Earth's Future*, **7** (10), 1136–1151. https://doi.org/10.1029/2019EF001249

39. Howard, E.M., H. Frenzel, F. Kessouri, L. Renault, D. Bianchi, J.C. McWilliams, and C. Deutsch, 2020: Attributing causes of future climate change in the California Current System with multimodel downscaling. *Global Biogeochemical Cycles*, **34** (11), e2020GB006646. https://doi.org/10.1029/2020gb006646

40. Jewett, L. and A. Romanou, 2017: Ch. 13. Ocean acidification and other ocean changes. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 364–392. https://doi.org/10.7930/j0qv3jqb

41. Siedlecki, S.A., D. Pilcher, E.M. Howard, C. Deutsch, P. MacCready, E.L. Norton, H. Frenzel, J. Newton, R.A. Feely, S.R. Alin, and T. Klinger, 2021: Coastal processes modify projections of some climate-driven stressors in the California Current System. *Biogeosciences*, **18** (9), 2871–2890. https://doi.org/10.5194/bg-18-2871-2021

42. Sunday, J.M., E. Howard, S. Siedlecki, D.J. Pilcher, C. Deutsch, P. MacCready, J. Newton, and T. Klinger, 2022: Biological sensitivities to high-resolution climate change projections in the California Current Marine Ecosystem. *Global Change Biology*, **28** (19), 5726–5740. https://doi.org/10.1111/gcb.16317

43. Feely, R.A., S.R. Alin, B. Carter, N. Bednaršek, B. Hales, F. Chan, T.M. Hill, B. Gaylord, E. Sanford, R.H. Byrne, C.L. Sabine, D. Greeley, and L. Juranek, 2016: Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuarine, Coastal and Shelf Science*, **183** (Part A), 260–270. https://doi.org/10.1016/j.ecss.2016.08.043

44. Doney, S.C., D.S. Busch, S.R. Cooley, and K.J. Kroeker, 2020: The impacts of ocean acidification on marine ecosystems and reliant human communities. *Annual Review of Environment and Resources*, **45**, 83–112. https://doi.org/10.1146/annurev-environ-012320-083019

45. Feely, R.A., R.R. Okazaki, W.-J. Cai, N. Bednaršek, S.R. Alin, R.H. Byrne, and A. Fassbender, 2018: The combined effects of acidification and hypoxia on pH and aragonite saturation in the coastal waters of the California Current Ecosystem and the northern Gulf of Mexico. *Continental Shelf Research*, **152**, 50–60. https://doi.org/10.1016/j.csr.2017.11.002

46. Pelletier, G., L. Bianucci, W. Long, T. Khangaonkar, T. Mohamedali, A. Ahmed, and C. Figueroa-Kaminsky, 2017: Salish Sea Model: Ocean Acidification Module and the Response to Regional Anthropogenic Nutrient Sources. Publication No. 17-03-009. State of Washington, Department of Ecology. https://apps.ecology.wa.gov/publications/documents/1703009.pdf

47. Gentemann, C.L., M.R. Fewings, and M. García-Reyes, 2017: Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. *Geophysical Research Letters*, **44** (1), 312–319. https://doi.org/10.1002/2016gl071039

48. Jones, T., J.K. Parrish, W.T. Peterson, E.P. Bjorkstedt, N.A. Bond, L.T. Ballance, V. Bowes, J.M. Hipfner, H.K. Burgess, J.E. Dolliver, K. Lindquist, J. Lindsey, H.M. Nevins, R.R. Robertson, J. Roletto, L. Wilson, T. Joyce, and J. Harvey, 2018: Massive mortality of a planktivorous seabird in response to a marine heatwave. *Geophysical Research Letters*, **45** (7), 3193–3202. https://doi.org/10.1002/2017gl076164

49. NMFS, 2022: 2019-2022 Gray Whale Unusual Mortality Event along the West Coast and Alaska. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://www.fisheries.noaa.gov/national/marine-life-distress/2019-2022-gray-whale-unusual-mortality-event-along-west-coast-and

50. Amaya, D.J., A.J. Miller, S.-P. Xie, and Y. Kosaka, 2020: Physical drivers of the summer 2019 North Pacific marine heatwave. *Nature Communications*, **11** (1), 1903. https://doi.org/10.1038/s41467-020-15820-w

51. Bond, N.A., M.F. Cronin, H. Freeland, and N. Mantua, 2015: Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, **42** (9), 3414–3420. https://doi.org/10.1002/2015gl063306

52. Oliver, E.C.J., J.A. Benthuysen, S. Darmaraki, M.G. Donat, A.J. Hobday, N.J. Holbrook, R.W. Schlegel, and A. Sen Gupta, 2021: Marine heatwaves. *Annual Review of Marine Science*, **13** (1), 313–342. https://doi.org/10.1146/annurev-marine-032720-095144

53. Peterson, W.T., J.L. Fisher, P.T. Strub, X. Du, C. Risien, J. Peterson, and C.T. Shaw, 2017: The pelagic ecosystem in the Northern California Current off Oregon during the 2014–2016 warm anomalies within the context of the past 20 years. *Journal of Geophysical Research: Oceans*, **122** (9), 7267–7290. https://doi.org/10.1002/2017jc012952

54. Trainer, V.L., S.K. Moore, G. Hallegraeff, R.M. Kudela, A. Clement, J.I. Mardones, and W.P. Cochlan, 2020: Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful Algae*, **91**, 101591. https://doi.org/10.1016/j.hal.2019.03.009

55. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

56. Newton, T.J., R. Weldon, I.M. Miller, D. Schmidt, G. Mauger, H. Morgan, and E. Grossman, 2021: An assessment of vertical land movement to support coastal hazards planning in Washington state. *Water*, **13** (3). https://doi.org/10.3390/w13030281

57. Taherkhani, M., S. Vitousek, P.L. Barnard, N. Frazer, T.R. Anderson, and C.H. Fletcher, 2020: Sea-level rise exponentially increases coastal flood frequency. *Scientific Reports*, **10** (1), 6466. https://doi.org/10.1038/s41598-020-62188-4

58. Miller, I.M., H. Morgan, G. Mauger, T. Newton, R. Weldon, D. Schmidt, M. Welch, and E. Grossman, 2018: Projected Sea Level Rise for Washington State—A 2018 Assessment. University of Washington, 24 pp. https://cig.uw.edu/projects/projected-sea-level-rise-for-washington-state-a-2018-assessment/

59. UW Climate Impacts Group, 2018: *An Unfair Share: Exploring the Disproportionate Risks from Climate Change Facing Washington State Communities*. University of Washington, Seattle, WA. https://cig.uw.edu/projects/an-unfair-share/

60. Voelkel, J., D. Hellman, R. Sakuma, and V. Shandas, 2018: Assessing vulnerability to urban heat: A study of disproportionate heat exposure and access to refuge by socio-demographic status in Portland, Oregon. *International Journal of Environmental Research and Public Health*, **15** (4), 640. https://doi.org/10.3390/ijerph15040640

61. Farrell, J., P.B. Burow, K. McConnell, J. Bayham, K. Whyte, and G. Koss, 2021: Effects of land dispossession and forced migration on Indigenous peoples in North America. *Science*, **374** (6567), 4943. https://doi.org/10.1126/science.abe4943

62. Lane, H.M., R. Morello-Frosch, J.D. Marshall, and J.S. Apte, 2022: Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environmental Science & Technology Letters*, **9** (4), 345–350. https://doi.org/10.1021/acs.estlett.1c01012

63. Alvarez, C.H., 2023: Structural racism as an environmental justice issue: A multilevel analysis of the state racism index and environmental health risk from air toxics. *Journal of Racial and Ethnic Health Disparities*, **10** (1), 244–258. https://doi.org/10.1007/s40615-021-01215-0

64. Colon, J., 2016: The Disproportionate Impacts of Climate Change on Communities of Color in Washington State. Front and Centered, 6 pp. https://frontandcentered.org/the-disproportionate-impacts-of-climate-change-on-communities-of-color-in-washington-state/

65. Digital Scholarship Lab and the National Community Reinvestment Coalition, 2020: Not even past: Social vulnerability and the legacy of redlining. In: *American Panorama.* Nelson, R. and E. Ayers, Eds. The Digital Scholarship Lab and the National Community Reinvestment Coalition. https://dsl.richmond.edu/socialvulnerability/

66. Priske, M., 2020: Environmental Racism and Economic Health Injustice: Exploring the LatinX Community in Eugene, Oregon. ArcGIS. https://storymaps.arcgis.com/stories/d519ab45cfc646438b8e91e846d674af

67. Bencivengo, A., E. Clark, M. Davies, E. Kushkowski, A. Loukides, F. Marten, A. Miller, L.I. Parker, H. Wise, and S. Witte, 2017: Vulnerability and Climate Change Adaptation Planning: Heat and Floods in Portland, Oregon. Reed College, Environmental Studies Department Junior Seminar, 62 pp. https://www.reed.edu/es/assets/es_300_2017_vulnerability-and-climate-change-adaptation-planning.pdf

68. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. https://doi.org/10.3390/cli8010012

69. Arnold, L., M.D. Scheuerell , and T. Busch Isaksen 2022: Mortality associated with extreme heat in Washington state: The historical and projected public health burden. *Atmosphere*, **13** (9), 1392. https://doi.org/10.3390/atmos13091392

70. Earth Economics, 2020: Urban Heat Island Analysis. Earth Economics, Tacoma, WA, 2 pp. https://cms.cityoftacoma.org/enviro/urbanforestry/tacomawa_heatislandanalysis.pdf

71. Schell, C.J., K. Dyson, T.L. Fuentes, S.D. Roches, N.C. Harris, D.S. Miller, C.A. Woelfle-Erskine, and M.R. Lambert, 2020: The ecological and evolutionary consequences of systemic racism in urban environments. *Science*, **369** (6510), 4497. https://doi.org/10.1126/science.aay4497

72. He, B.-J., J. Zhu, D.-X. Zhao, Z.-H. Gou, J.-D. Qi, and J. Wang, 2019: Co-benefits approach: Opportunities for implementing sponge city and urban heat island mitigation. *Land Use Policy*, **86**, 147–157. https://doi.org/10.1016/j.landusepol.2019.05.003

73. Richards, D.R. and P.J. Edwards, 2018: Using water management infrastructure to address both flood risk and the urban heat island. *International Journal of Water Resources Development*, **34** (4), 490–498. https://doi.org/10.1080/07900627.2017.1357538

74. Fischer, A.P., 2019: Pathways of adaptation to external stressors in coastal natural-resource-dependent communities: Implications for climate change. *World Development*, **108**, 235–248. https://doi.org/10.1016/j.worlddev.2017.12.007

75. Childs, M.L., J. Li, J. Wen, S. Heft-Neal, A. Driscoll, S. Wang, C.F. Gould, M. Qiu, J. Burney, and M. Burke, 2022: Daily local-level estimates of ambient wildfire smoke/$PM_{2.5}$ for the contiguous US. *Environmental Science & Technology*, **56** (19), 13607–13621. https://doi.org/10.1021/acs.est.2c02934

76. Tigchelaar, M., D.S. Battisti, and J.T. Spector, 2020: Work adaptations insufficient to address growing heat risk for U.S. agricultural workers. *Environmental Research Letters*, **15** (9), 094035. https://doi.org/10.1088/1748-9326/ab86f4

77. Calkins, M.M., D. Bonauto, A. Hajat, M. Lieblich, N. Seixas, L. Sheppard, and J.T. Spector, 2019: A case-crossover study of heat exposure and injury risk among outdoor construction workers in Washington State. *Scandinavian Journal of Work, Environment & Health*, **45** (6), 588–599. https://doi.org/10.5271/sjweh.3814

78. Oregon Health Authority, 2020: Climate and Health in Oregon 2020 Report. Oregon Health Authority, Public Health Division. https://www.oregon.gov/oha/ph/healthyenvironments/climatechange/documents/2020/climate%20and%20health%20in%20oregon%202020%20-%20full%20report.pdf

79. Miller, A.B., P.L. Winter, J.J. Sánchez, D.L. Peterson, and J.W. Smith, 2022: Climate change and recreation in the western United States: Effects and opportunities for adaptation. *Journal of Forestry*, **120** (4), 453–472. https://doi.org/10.1093/jofore/fvab072

80. Petersen-Rockney, M., P. Baur, A. Guzman, S.F. Bender, A. Calo, F. Castillo, K. De Master, A. Dumont, K. Esquivel, C. Kremen, J. LaChance, M. Mooshammer, J. Ory, M.J. Price, Y. Socolar, P. Stanley, A. Iles, and T. Bowles, 2021: Narrow and brittle or broad and nimble? Comparing adaptive capacity in simplifying and diversifying farming systems. *Frontiers in Sustainable Food Systems*, **5**, 564900. https://doi.org/10.3389/fsufs.2021.564900

81. Weiler, A.M., 2022: Farmworkers, climate change, and "converging crises". *Gastronomica*, **22** (1), 44–49. https://doi.org/10.1525/gfc.2022.22.1.44

82. Lavoie, A.L., K. Dentzman, and C.B. Wardropper, 2021: Using diffusion of innovations theory to understand agricultural producer perspectives on cover cropping in the inland Pacific Northwest, USA. *Renewable Agriculture and Food Systems*, **36** (4), 384–395. https://doi.org/10.1017/s1742170520000423

83. Roesch-McNally, G., A. Garrett, and M. Fery, 2020: Assessing perceptions of climate risk and adaptation among small farmers in Oregon's Willamette Valley. *Renewable Agriculture and Food Systems*, **35** (6), 626–630. https://doi.org/10.1017/s1742170519000267

84. Wardropper, C.B., J.P. Angerer, M. Burnham, M.E. Fernández-Giménez, V.S. Jansen, J.W. Karl, K. Lee, and K. Wollstein, 2021: Improving rangeland climate services for ranchers and pastoralists with social science. *Current Opinion in Environmental Sustainability*, **52**, 82–91. https://doi.org/10.1016/j.cosust.2021.07.001

85. Boag, A.E., J. Hartter, L.C. Hamilton, N.D. Christoffersen, F.R. Stevens, M.W. Palace, and M.J. Ducey, 2018: Climate change beliefs and forest management in eastern Oregon: Implications for individual adaptive capacity. *Ecology and Society*, **23** (4). https://doi.org/10.5751/es-10355-230401

86. Haltinner, K. and D. Sarathchandra, 2021: Considering attitudinal uncertainty in the climate change skepticism continuum. *Global Environmental Change*, **68**, 102243. https://doi.org/10.1016/j.gloenvcha.2021.102243

87. Maas, A., C. Wardropper, G. Roesch-McNally, and J. Abatzoglou, 2020: A (mis)alignment of farmer experience and perceptions of climate change in the U.S. inland pacific northwest. *Climatic Change*, **162** (3), 1011–1029. https://doi.org/10.1007/s10584-020-02713-6

88. Hand, J.P., 2008: Global climate change: A serious threat to Native American lands and culture. *Environmental Law Reporter-News & Analysis*, **38**, 10329. https://heinonline.org/HOL/LandingPage?handle=hein.journals/elrna38&div=28&id=&page=

89. Vinyeta, K. and K. Lynn, 2013: Exploring the Role of Traditional Ecological Knowledge in Climate Change Initiatives. Gen. Tech. Rep. PNW-GTR-879. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 37 pp. https://doi.org/10.2737/pnw-gtr-879

90. Burkett, M., R.R.M. Verchick, and D. Flores, 2017: Reaching Higher Ground: Avenues to Secure and Manage New Land for Communities Displaced by Climate Change. Research Paper No. 2017-07. Loyola University New Orleans College of Law, Center for Progressive Reform. https://ssrn.com/abstract=3034040

91. Ford, J.K. and E. Giles, 2015: Climate change adaptation in Indian country: Tribal regulation of reservation lands and natural resources. *William Mitchell Law Review*, **41** (2), 519–551. http://open.mitchellhamline.edu/wmlr/vol41/iss2/3/

92. Watkinson-Schutten, M., 2022: Decolonizing climate adaptation by reacquiring fractionated tribal lands. In: *The Oxford Handbook of Indigenous Sociology*. Walter, M., T. Kukutai, A.A. Gonzales, and R. Henry, Eds. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780197528778.013.42

93. Maldonado, J., D. Antrobus, C. Comardelle, S.R. Cox, L. Laukea, C. Jones, P. Keys, H. Mullen, M. Neale, and D. Sambo Dorough, 2021: Ch. 10. Protection-in-place & community-led relocation. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 241–259. http://nau.edu/stacc2021

94. Jantarasami, L.C., R. Novak, R. Delgado, E. Marino, S. McNeeley, C. Narducci, J. Raymond-Yakoubian, L. Singletary, and K.P. Whyte, 2018: Ch. 15. Tribes and Indigenous Peoples. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program,, Washington, DC, USA, 572–603. https://doi.org/10.7930/nca4.2018.ch15

95. Lynn, K., J. Daigle, J. Hoffman, F. Lake, N. Michelle, D. Ranco, C. Viles, G. Voggesser, and P. Williams, 2014: Ch. 4. The impacts of climate change on tribal traditional foods. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., B. Colombi, and R. Pandya, Eds. Springer, Cham, Switzerland, 37–48. https://doi.org/10.1007/978-3-319-05266-3_4

96. Prevéy, J.S., L.E. Parker, C.A. Harrington, C.T. Lamb, and M.F. Proctor, 2020: Climate change shifts in habitat suitability and phenology of huckleberry (*Vaccinium membranaceum*). *Agricultural and Forest Meteorology*, **280**, 107803. https://doi.org/10.1016/j.agrformet.2019.107803

97. Front and Centered, 2020: Accelerating a Just Transition in Washington State: Climate Justice Strategies from the Frontlines. Front and Centered, 6 pp. https://frontandcentered.org/accelerating-a-just-transition-in-wa-state/

98. Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372** (6549), 8054. https://doi.org/10.1126/science.abc8054

99. Hellman, D. and V. Shandas, 2020: Community Resilience to Climate Change: Theory, Research and Practice. Portland State University. https://doi.org/10.15760/pdxopen-24

100. Makido, Y., D. Hellman, and V. Shandas, 2019: Nature-based designs to mitigate urban heat: The efficacy of green infrastructure treatments in Portland, Oregon. *Atmosphere*, **10** (5), 282. https://doi.org/10.3390/atmos10050282

101. Puget Sound Sage, 2020: Powering the Transition: Community Priorities for a Renewable and Equitable Future. Puget Sound Sage. https://pugetsoundsage.org/research/clean-healthy-environment/community-energy/

102. Blazina, A. and K. Davis, 2022: The Wildland-Urban Interface: Mapping Washington State's Fastest-Growing Environment. Washington State Department of Natural Resources. https://storymaps.arcgis.com/stories/7016c437623a445997c072a05e26afbb

103. Mockrin, M.H., D. Helmers, S. Martinuzzi, T.J. Hawbaker, and V.C. Radeloff, 2022: Growth of the wildland-urban interface within and around U.S. National Forests and Grasslands, 1990–2010. *Landscape and Urban Planning*, **218**, 104283. https://doi.org/10.1016/j.landurbplan.2021.104283

104. Radeloff, V.C., D.P. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar-Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, and S.I. Stewart, 2018: Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (13), 3314–3319. https://doi.org/10.1073/pnas.1718850115

105. City of Boise, 2021: Boise's Climate Action Roadmap: Our Community's Plan for Climate Action. City of Boise. https://www.cityofboise.org/media/15045/boise-climate-roadmap.pdf

106. King County Climate Equity Community Task Force, 2020: Section II: Sustainable & resilient frontline communities. In: *King County 2020 Strategic Climate Action Plan*. Stroble, J. and S. Rahman, Eds., King County, WA. https://your.kingcounty.gov/dnrp/climate/documents/scap-2020-approved/2020-scap-sustainable-and-resilient-frontline-communities-section.pdf

107. Germain, S.J. and J.A. Lutz, 2020: Climate extremes may be more important than climate means when predicting species range shifts. *Climatic Change*, **163** (1), 579–598. https://doi.org/10.1007/s10584-020-02868-2

108. Noy-Meir, I., 1973: Desert ecosystems: Environment and producers. *Annual Review of Ecology and Systematics*, **4** (1), 25–51. https://doi.org/10.1146/annurev.es.04.110173.000325

109. Rangwala, I., W. Moss, J. Wolken, R. Rondeau, K. Newlon, J. Guinotte, and W.R. Travis, 2021: Uncertainty, complexity and constraints: How do we robustly assess biological responses under a rapidly changing climate? *Climate*, **9** (12), 177. https://doi.org/10.3390/cli9120177

110. Singer, M.C., 2017: Shifts in time and space interact as climate warms. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (49), 12848–12850. https://doi.org/10.1073/pnas.1718334114

111. Fogarty, F.A., D.R. Cayan, L.L. DeHaan, and E. Fleishman, 2020: Associations of breeding-bird abundance with climate vary among species and trait-based groups in southern California. *PLoS ONE*, **15** (3), e0230614. https://doi.org/10.1371/journal.pone.0230614

112. Harsch, M.A. and J. HilleRisLambers, 2016: Climate warming and seasonal precipitation change interact to limit species distribution shifts across western North America. *PLoS ONE*, **11** (7), e0159184. https://doi.org/10.1371/journal.pone.0159184

113. Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (42), 11770–11775. https://doi.org/10.1073/pnas.1607171113

114. Alizadeh, M.R., J.T. Abatzoglou, C.H. Luce, J.F. Adamowski, A. Farid, and M. Sadegh, 2021: Warming enabled upslope advance in western US forest fires. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (22), e2009717118. https://doi.org/10.1073/pnas.2009717118

115. Holden, Z.A., A. Swanson, C.H. Luce, W.M. Jolly, M. Maneta, J.W. Oyler, D.A. Warren, R. Parsons, and D. Affleck, 2018: Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (36), E8349–E8357. https://doi.org/10.1073/pnas.1802316115

116. Alizadeh, M.R., J. Adamowski, M.R. Nikoo, A. AghaKouchak, P. Dennison, and M. Sadegh, 2020: A century of observations reveals increasing likelihood of continental-scale compound dry-hot extremes. *Science Advances*, **6** (39), 4571. https://doi.org/10.1126/sciadv.aaz4571

117. Halofsky, J.E., D.L. Peterson, and B.J. Harvey, 2020: Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, **16** (1), 4. https://doi.org/10.1186/s42408-019-0062-8

118. Coop, J.D., S.A. Parks, C.S. Stevens-Rumann, S.D. Crausbay, P.E. Higuera, M.D. Hurteau, A. Tepley, E. Whitman, T. Assal, B.M. Collins, K.T. Davis, S. Dobrowski, D.A. Falk, P.J. Fornwalt, P.Z. Fulé, B.J. Harvey, V.R. Kane, C.E. Littlefield, E.Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K.C. Rodman, 2020: Wildfire-driven forest conversion in western North American landscapes. *BioScience*, **70** (8), 659–673. https://doi.org/10.1093/biosci/biaa061

119. Parks, S.A., S.Z. Dobrowski, J.D. Shaw, and C. Miller, 2019: Living on the edge: Trailing edge forests at risk of fire-facilitated conversion to non-forest. *Ecosphere*, **10** (3), e02651. https://doi.org/10.1002/ecs2.2651

120. Bradley, B.A., C.A. Curtis, and J.C. Chambers, 2016: Ch. 9. *Bromus* response to climate and projected changes with climate change. In: *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US: Causes, Consequences, and Management Implications*. Germino, M.J., J.C. Chambers, and C.S. Brown, Eds. Springer, Cham, Switzerland, 257–274. https://doi.org/10.1007/978-3-319-24930-8_9

121. Williamson, M.A., E. Fleishman, R.C. Mac Nally, J.C. Chambers, B.A. Bradley, D.S. Dobkin, D.I. Board, F.A. Fogarty, N. Horning, M. Leu, and M. Wohlfeil Zillig, 2020: Fire, livestock grazing, topography, and precipitation affect occurrence and prevalence of cheatgrass (*Bromus tectorum*) in the Central Great Basin, USA. *Biological Invasions*, **22** (2), 663–680. https://doi.org/10.1007/s10530-019-02120-8

122. Mack, R.N. and J.N. Thompson, 1982: Evolution in steppe with few large, hooved mammals. *The American Naturalist*, **119** (6), 757–773. http://www.jstor.org/stable/2460961

123. Balch, J.K., B.A. Bradley, J.T. Abatzoglou, R.C. Nagy, E.J. Fusco, and A.L. Mahood, 2017: Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (11), 2946–2951. https://doi.org/10.1073/pnas.1617394114

124. Gervais, J.A., R. Kovach, A. Sepulveda, R. Al-Chokhachy, J. Joseph Giersch, and C.C. Muhlfeld, 2020: Climate-induced expansions of invasive species in the Pacific Northwest, North America: A synthesis of observations and projections. *Biological Invasions*, **22** (7), 2163–2183. https://doi.org/10.1007/s10530-020-02244-2

125. Abrams, J., H. Huber-Stearns, M. Steen-Adams, E.J. Davis, C. Bone, M.F. Nelson, and C. Moseley, 2021: Adaptive governance in a complex social-ecological context: Emergent responses to a native forest insect outbreak. *Sustainability Science*, **16** (1), 53–68. https://doi.org/10.1007/s11625-020-00843-5

126. Agne, M.C., P.A. Beedlow, D.C. Shaw, D.R. Woodruff, E.H. Lee, S.P. Cline, and R.L. Comeleo, 2018: Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. *Forest Ecology and Management*, **409**, 317–332. https://doi.org/10.1016/j.foreco.2017.11.004

127. Bentz, B.J., J. Régnière, C.J. Fettig, E.M. Hansen, J.L. Hayes, J.A. Hicke, R.G. Kelsey, J.F. Negrón, and S.J. Seybold, 2010: Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. *BioScience*, **60** (8), 602–613. https://doi.org/10.1525/bio.2010.60.8.6

128. Elliott, J., S.I. Passy, K.L. Pound, G. Merritt, S. Polkowske, and C.A. Larson, 2022: Strong but heterogeneous distributional responses to climate change are projected for temperate and semi-arid stream vertebrates. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **32** (8), 1291–1305. https://doi.org/10.1002/aqc.3805

129. Jacobs, G.R., R.F. Thurow, J.M. Buffington, D.J. Isaak, and S.J. Wenger, 2021: Climate, fire regime, geomorphology, and conspecifics influence the spatial distribution of Chinook salmon Redds. *Transactions of the American Fisheries Society*, **150** (1), 8–23. https://doi.org/10.1002/tafs.10270

130. Reid, A.J., A.K. Carlson, I.F. Creed, E.J. Eliason, P.A. Gell, P.T.J. Johnson, K.A. Kidd, T.J. MacCormack, J.D. Olden, S.J. Ormerod, J.P. Smol, W.W. Taylor, K. Tockner, J.C. Vermaire, D. Dudgeon, and S.J. Cooke, 2019: Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews*, **94** (3), 849–873. https://doi.org/10.1111/brv.12480

131. Wenger, S.J., D.J. Isaak, C.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Elsner, B.E. Rieman, A.F. Hamlet, and J.E. Williams, 2011: Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **108** (34), 14175–14180. https://doi.org/10.1073/pnas.1103097108

132. Al-Chokhachy, R., M. Lien, B.B. Shepard, and B. High, 2021: The interactive effects of stream temperature, stream size, and non-native species on Yellowstone cutthroat trout. *Canadian Journal of Fisheries and Aquatic Sciences*, **78** (8), 1073–1083. https://doi.org/10.1139/cjfas-2020-0408

133. Rubenson, E.S., D.J. Lawrence, and J.D. Olden, 2020: Threats to rearing juvenile Chinook salmon from nonnative smallmouth bass inferred from stable isotope and fatty acid biomarkers. *Transactions of the American Fisheries Society*, **149** (3), 350–363. https://doi.org/10.1002/tafs.10237

134. Rubenson, E.S. and J.D. Olden, 2020: An invader in salmonid rearing habitat: Current and future distributions of smallmouth bass (*Micropterus dolomieu*) in the Columbia River Basin. *Canadian Journal of Fisheries and Aquatic Sciences*, **77** (2), 314–325. https://doi.org/10.1139/cjfas-2018-0357

135. Freeman, M.C., K.R. Bestgen, D. Carlisle, E.A. Frimpong, N.R. Franssen, K.B. Gido, E. Irwin, Y. Kanno, C. Luce, S. Kyle McKay, M.C. Mims, J.D. Olden, N. LeRoy Poff, D.L. Propst, L. Rack, A.H. Roy, E.S. Stowe, A. Walters, and S.J. Wenger, 2022: Toward improved understanding of streamflow effects on freshwater fishes. *Fisheries*, **47** (7), 290–298. https://doi.org/10.1002/fsh.10731

136. Goode, J.R., J.M. Buffington, D. Tonina, D.J. Isaak, R.F. Thurow, S. Wenger, D. Nagel, C. Luce, D. Tetzlaff, and C. Soulsby, 2013: Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. *Hydrological Processes*, **27** (5), 750–765. https://doi.org/10.1002/hyp.9728

137. Gould, G.K., M. Liu, M.E. Barber, K.A. Cherkauer, P.R. Robichaud, and J.C. Adam, 2016: The effects of climate change and extreme wildfire events on runoff erosion over a mountain watershed. *Journal of Hydrology*, **536**, 74–91. https://doi.org/10.1016/j.jhydrol.2016.02.025

138. Nicol, C.L., J.C. Jorgensen, C.B. Fogel, B. Timpane-Padgham, and T.J. Beechie, 2022: Spatially overlapping salmon species have varied population response to early life history mortality from increased peak flows. *Canadian Journal of Fisheries and Aquatic Sciences*, **79** (2), 342–351. https://doi.org/10.1139/cjfas-2021-0038

139. Srivastava, A., E.S. Brooks, M. Dobre, W.J. Elliot, J.Q. Wu, D.C. Flanagan, J.A. Gravelle, and T.E. Link, 2020: Modeling forest management effects on water and sediment yield from nested, paired watersheds in the interior Pacific Northwest, USA using WEPP. *Science of The Total Environment*, **701**, 134877. https://doi.org/10.1016/j.scitotenv.2019.134877

140. Dunham, J.B., M.K. Young, R.E. Gresswell, and B.E. Rieman, 2003: Effects of fire on fish populations: Landscape perspectives on persistence of native fishes and nonnative fish invasions. *Forest Ecology and Management*, **178** (1), 183–196. https://doi.org/10.1016/s0378-1127(03)00061-6

141. Isaak, D.J., C.H. Luce, B.E. Rieman, D.E. Nagel, E.E. Peterson, D.L. Horan, S. Parkes, and G.L. Chandler, 2010: Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. *Ecological Applications*, **20** (5), 1350–1371. https://doi.org/10.1890/09-0822.1

142. Goode, J.R., C.H. Luce, and J.M. Buffington, 2012: Enhanced sediment delivery in a changing climate in semi-arid mountain basins: Implications for water resource management and aquatic habitat in the northern Rocky Mountains. *Geomorphology*, **139**, 1–15. https://doi.org/10.1016/j.geomorph.2011.06.021

143. Maturana, O., D. Tonina, J.A. McKean, J.M. Buffington, C.H. Luce, and D. Caamaño, 2014: Modeling the effects of pulsed versus chronic sand inputs on salmonid spawning habitat in a low-gradient gravel-bed river. *Earth Surface Processes and Landforms*, **39** (7), 877–889. https://doi.org/10.1002/esp.3491

144. Rieman, B., D. Lee, D. Burns, R. Gresswell, M. Young, R. Stowell, J. Rinne, and P. Howell, 2003: Status of native fishes in the western United States and issues for fire and fuels management. *Forest Ecology and Management*, **178** (1), 197–211. https://doi.org/10.1016/s0378-1127(03)00062-8

145. Free, C.M., S.C. Anderson, E.A. Hellmers, B.A. Muhling, M.O. Navarro, K. Richerson, L.A. Rogers, W.H. Satterthwaite, A.R. Thompson, J.M. Burt, S.D. Gaines, K.N. Marshall, J.W. White, and L.F. Bellquist, 2023: Impact of the 2014–2016 marine heatwave on US and Canada West Coast fisheries: Surprises and lessons from key case studies. *Fish and Fisheries*, **24** (4), 652–674. https://doi.org/10.1111/faf.12753

146. Morgan, C.A., B.R. Beckman, L.A. Weitkamp, and K.L. Fresh, 2019: Recent ecosystem disturbance in the Northern California Current. *Fisheries*, **44** (10), 465–474. https://doi.org/10.1002/fsh.10273

147. Shanks, A.L., L.K. Rasmuson, J.R. Valley, M.A. Jarvis, C. Salant, D.A. Sutherland, E.I. Lamont, M.A.H. Hainey, and R.B. Emlet, 2020: Marine heat waves, climate change, and failed spawning by coastal invertebrates. *Limnology and Oceanography*, **65** (3), 627–636. https://doi.org/10.1002/lno.11331

148. McCabe, R.M., B.M. Hickey, R.M. Kudela, K.A. Lefebvre, N.G. Adams, B.D. Bill, F.M.D. Gulland, R.E. Thomson, W.P. Cochlan, and V.L. Trainer, 2016: An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, **43** (19), 10366–10376. https://doi.org/10.1002/2016gl070023

149. Akmajian, A.M., J.J. Scordino, and A. Acevedo-Gutiérrez, 2017: Year-round algal toxin exposure in free-ranging sea lions. *Marine Ecology Progress Series*, **583**, 243–258. https://doi.org/10.3354/meps12345

150. Piatt, J.F., J.K. Parrish, H.M. Renner, S.K. Schoen, T.T. Jones, M.L. Arimitsu, K.J. Kuletz, B. Bodenstein, M. García-Reyes, R.S. Duerr, R.M. Corcoran, R.S.A. Kaler, G.J. McChesney, R.T. Golightly, H.A. Coletti, R.M. Suryan, H.K. Burgess, J. Lindsey, K. Lindquist, P.M. Warzybok, J. Jahncke, J. Roletto, and W.J. Sydeman, 2020: Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014–2016. *PLoS ONE*, **15** (1), e0226087. https://doi.org/10.1371/journal.pone.0226087

151. Ford, M.J., 2022: Biological Viability Assessment Update for Pacific Salmon and Steelhead Listed Under the Endangered Species Act: Pacific Northwest. NOAA Technical Memorandum NMFS-NWFSC-171. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://doi.org/10.25923/kq2n-ke70

152. Raymond, W.W., J.S. Barber, M.N. Dethier, H.A. Hayford, C.D.G. Harley, T.L. King, B. Paul, C.A. Speck, E.D. Tobin, A.E.T. Raymond, and P.S. McDonald, 2022: Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. *Ecology*, **103** (10), e3798. https://doi.org/10.1002/ecy.3798

153. Frölicher, T.L., E.M. Fischer, and N. Gruber, 2018: Marine heatwaves under global warming. *Nature*, **560** (7718), 360–364. https://doi.org/10.1038/s41586-018-0383-9

154. Smith, K.E., M.T. Burrows, A.J. Hobday, N.G. King, P.J. Moore, A. Sen Gupta, M.S. Thomsen, T. Wernberg, and D.A. Smale, 2023: Biological impacts of marine heatwaves. *Annual Review of Marine Science*, **15** (1), 119–145. https://doi.org/10.1146/annurev-marine-032122-121437

155. Samhouri, J.F., B.E. Feist, M.C. Fisher, O. Liu, S.M. Woodman, B. Abrahms, K.A. Forney, E.L. Hazen, D. Lawson, J. Redfern, and L.E. Saez, 2021: Marine heatwave challenges solutions to human-wildlife conflict. *Proceedings of the Royal Society B: Biological Sciences*, **288** (1964), 20211607. https://doi.org/10.1098/rspb.2021.1607

156. Cline, T.J., J. Ohlberger, and D.E. Schindler, 2019: Effects of warming climate and competition in the ocean for life-histories of Pacific salmon. *Nature Ecology & Evolution*, **3** (6), 935–942. https://doi.org/10.1038/s41559-019-0901-7

157. Litzow, M.A., F.J. Mueter, and A.J. Hobday, 2014: Reassessing regime shifts in the North Pacific: Incremental climate change and commercial fishing are necessary for explaining decadal-scale biological variability. *Global Change Biology*, **20** (1), 38–50. https://doi.org/10.1111/gcb.12373

158. Ohlberger, J., E.J. Ward, D.E. Schindler, and B. Lewis, 2018: Demographic changes in Chinook salmon across the northeast Pacific Ocean. *Fish and Fisheries*, **19** (3), 533–546. https://doi.org/10.1111/faf.12272

159. Welch, D.W., A.D. Porter, and E.L. Rechisky, 2021: A synthesis of the coast-wide decline in survival of West Coast Chinook salmon (*Oncorhynchus tshawytscha*, Salmonidae). *Fish and Fisheries*, **22** (1), 194–211. https://doi.org/10.1111/faf.12514

160. Crozier, L.G., B.J. Burke, B.E. Chasco, D.L. Widener, and R.W. Zabel, 2021: Climate change threatens Chinook salmon throughout their life cycle. *Communications Biology*, **4** (1), 222. https://doi.org/10.1038/s42003-021-01734-w

161. Crozier, L.G., J.E. Siegel, L.E. Wiesebron, E.M. Trujillo, B.J. Burke, B.P. Sandford, and D.L. Widener, 2020: Snake River sockeye and Chinook salmon in a changing climate: Implications for upstream migration survival during recent extreme and future climates. *PLoS ONE*, **15** (9), e0238886. https://doi.org/10.1371/journal.pone.0238886

162. Isaak, D.J., C.H. Luce, D.L. Horan, G.L. Chandler, S.P. Wollrab, and D.E. Nagel, 2018: Global warming of salmon and trout rivers in the northwestern U.S.: Road to ruin or path through purgatory? *Transactions of the American Fisheries Society*, **147** (3), 566–587. https://doi.org/10.1002/tafs.10059

163. Isaak, D.J., S.J. Wenger, E.E. Peterson, J.M. Ver Hoef, D.E. Nagel, C.H. Luce, S.W. Hostetler, J.B. Dunham, B.B. Roper, S.P. Wollrab, G.L. Chandler, D.L. Horan, and S. Parkes-Payne, 2017: The NorWeST summer stream temperature model and scenarios for the Western U.S.: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. *Water Resources Research*, **53** (11), 9181–9205. https://doi.org/10.1002/2017wr020969

164. Keefer, M.L., T.S. Clabough, M.A. Jepson, E.L. Johnson, C.A. Peery, and C.C. Caudill, 2018: Thermal exposure of adult Chinook salmon and steelhead: Diverse behavioral strategies in a large and warming river system. *PLoS ONE*, **13** (9), e0204274. https://doi.org/10.1371/journal.pone.0204274

165. Zhang, X., H.-Y. Li, Z.D. Deng, L.R. Leung, J.R. Skalski, and S.J. Cooke, 2019: On the variable effects of climate change on Pacific salmon. *Ecological Modelling*, **397**, 95–106. https://doi.org/10.1016/j.ecolmodel.2019.02.002

166. Moore, S.K., J.A. Johnstone, N.S. Banas, and E.P. Salathé, 2015: Present-day and future climate pathways affecting *Alexandrium* blooms in Puget Sound, WA, USA. *Harmful Algae*, **48**, 1–11. https://doi.org/10.1016/j.hal.2015.06.008

167. Ralston, D.K. and S.K. Moore, 2020: Modeling harmful algal blooms in a changing climate. *Harmful Algae*, **91**, 101729. https://doi.org/10.1016/j.hal.2019.101729

168. Munsch, S.H., C.M. Greene, N.J. Mantua, and W.H. Satterthwaite, 2022: One hundred-seventy years of stressors erode salmon fishery climate resilience in California's warming landscape. *Global Change Biology*, **28** (7), 2183–2201. https://doi.org/10.1111/gcb.16029

169. Sullaway, G.H., A.O. Shelton, and J.F. Samhouri, 2021: Synchrony erodes spatial portfolios of an anadromous fish and alters availability for resource users. *Journal of Animal Ecology*, **90** (11), 2692–2703. https://doi.org/10.1111/1365-2656.13575

170. Crozier, L.G., M.M. McClure, T. Beechie, S.J. Bograd, D.A. Boughton, M. Carr, T.D. Cooney, J.B. Dunham, C.M. Greene, M.A. Haltuch, E.L. Hazen, D.M. Holzer, D.D. Huff, R.C. Johnson, C.E. Jordan, I.C. Kaplan, S.T. Lindley, N.J. Mantua, P.B. Moyle, J.M. Myers, M.W. Nelson, B.C. Spence, L.A. Weitkamp, T.H. Williams, and E. Willis-Norton, 2019: Climate vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. *PLoS ONE*, **14** (7), e0217711. https://doi.org/10.1371/journal.pone.0217711

171. WCR, 2015: ESA Recovery Plan for Snake River Sockeye Salmon (*Oncorhynchus nerka*). National Oceanic and Atmospheric Administration, National Marine Fisheries Service, West Coast Region. https://repository.library.noaa.gov/view/noaa/16001

172. Waples, R.S., O.W. Johnson, and R.P. Jones Jr., 1991: Status Review for Snake River Sockeye Salmon. NOAA Technical Memorandum NMFS F/NWC-19. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://repository.library.noaa.gov/view/noaa/21168

173. Johnson, E.L., C.C. Kozfkay, J.H. Powell, M.P. Peterson, D.J. Baker, J.A. Heindel, K.E. Plaster, J.L. McCormick, and P.A. Kline, 2020: Evaluating artificial propagation release strategies for recovering endangered Snake River sockeye salmon. *North American Journal of Aquaculture*, **82** (3), 331–344. https://doi.org/10.1002/naaq.10148

174. Kozfkay, C.C., M. Peterson, B.P. Sandford, E.L. Johnson, and P. Kline, 2019: The productivity and viability of Snake River sockeye salmon hatchery adults released into Redfish Lake, Idaho. *Transactions of the American Fisheries Society*, **148** (2), 308–323. https://doi.org/10.1002/tafs.10136

175. Selbie, D.T., B.A. Lewis, J.P. Smol, and B.P. Finney, 2007: Long-term population dynamics of the endangered Snake River sockeye salmon: Evidence of past influences on stock decline and impediments to recovery. *Transactions of the American Fisheries Society*, **136** (3), 800–821. https://doi.org/10.1577/t06-100.1

176. Good, T.P., R.S. Waples, and P. Adams, 2005: Updated Status of Federally Listed ESUs of West Coast Salmon and Steelhead. NOAA Technical Memorandum NMFS-NWFSC-66. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center, 598 pp. https://repository.library.noaa.gov/view/noaa/3413

177. Kalinowski, S.T., D.M. Van Doornik, C.C. Kozfkay, and R.S. Waples, 2012: Genetic diversity in the Snake River sockeye salmon captive broodstock program as estimated from broodstock records. *Conservation Genetics*, **13** (5), 1183–1193. https://doi.org/10.1007/s10592-012-0363-9

178. Crozier, L.G., L.E. Weisebron, J.E. Siegel, B.J. Burke, T.M. Marsh, B.P. Sandford, and D.L. Widener, 2018: Passage and Survival of Adult Snake River Sockeye Salmon Within and Upstream from the Federal Columbia River Power System: 2008–2017 National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center, Fish Ecology Division, Seattle, WA. https://www.webapps.nwfsc.noaa.gov/assets/26/9567_03132020_144513_Crozier.et.al.2018-Adult-Sockeye-2008-2017-USACE.pdf

179. NMFS, 2016: 2015 Adult Sockeye Salmon Passage Report. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://www.columbiariverkeeper.org/sites/default/files/2017/08/8.pdf

180. WCR, 2021: Endangered Species Act Section 7 Formal Consultation and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Consultation for Authorizing Operation and Maintenance of Water Diversions Located on the Salmon-Challis National Forest in the Lemhi River Watershed, HUC 17060204, Lemhi County, Idaho. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, West Coast Region. https://doi.org/10.25923/r94p-xe17

181. Walters, A.W., K.K. Bartz, and M.M. Mcclure, 2013: Interactive effects of water diversion and climate change for juvenile Chinook salmon in the Lemhi River Basin (U.S.A.). *Conservation Biology*, **27** (6), 1179–1189. https://doi.org/10.1111/cobi.12170

182. Evans, M.L., A.E. Kohler, R.G. Griswold, K.A. Tardy, K.R. Eaton, and J.D. Ebel, 2020: Salmon-mediated nutrient flux in Snake River sockeye salmon nursery lakes: The influence of depressed population size and hatchery supplementation. *Lake and Reservoir Management*, **36** (1), 75–86. https://doi.org/10.1080/10402381.2019.1654571

183. Krueger, C.C., W.W. Taylor, and S.-J. Youn, 2019: Ch. 1. Fishery management success: Action, collaboration, communication, and commitment. In: *From Catastrophe to Recovery: Stories of Fishery Management Success*. Krueger, C.C., W.W. Taylor, and S.-J. Youn, Eds. American Fisheries Society. https://doi.org/10.47886/9781934874554.ch1

184. Crozier, L.G., M.D. Scheuerell, and R.W. Zabel, 2011: Using time series analysis to characterize evolutionary and plastic responses to environmental change: A case study of a shift toward earlier migration date in sockeye salmon. *The American Naturalist*, **178** (6), 755–773. https://doi.org/10.1086/662669

185. Quinn, T.P. and D.J. Adams, 1996: Environmental changes affecting the migratory timing of American shad and sockeye salmon. *Ecology*, **77** (4), 1151–1162. https://doi.org/10.2307/2265584

186. Bennett, J.M., R.H. Clarke, G.F.B. Horrocks, J.R. Thomson, and R. Mac Nally, 2015: Climate drying amplifies the effects of land-use change and interspecific interactions on birds. *Landscape Ecology*, **30** (10), 2031–2043. https://doi.org/10.1007/s10980-015-0229-x

187. Habel, J.C. and F.E. Zachos, 2012: Habitat fragmentation versus fragmented habitats. *Biodiversity and Conservation*, **21** (11), 2987–2990. https://doi.org/10.1007/s10531-012-0349-4

188. Carja, O. and J.B. Plotkin, 2019: Evolutionary rescue through partly heritable phenotypic variability. *Genetics*, **211** (3), 977–988. https://doi.org/10.1534/genetics.118.301758

189. Nimmo, D.G., A. Haslem, J.Q. Radford, M. Hall, and A.F. Bennett, 2016: Riparian tree cover enhances the resistance and stability of woodland bird communities during an extreme climatic event. *Journal of Applied Ecology*, **53** (2), 449–458. https://doi.org/10.1111/1365-2664.12535

190. Thompson, L.M., L.L. Thurman, C.N. Cook, E.A. Beever, C.M. Sgrò, A. Battles, C.A. Botero, J.E. Gross, K.R. Hall, A.P. Hendry, A.A. Hoffmann, C. Hoving, O.E. LeDee, C. Mengelt, A.B. Nicotra, R.A. Niver, F. Pérez-Jvostov, R.M. Quiñones, G.W. Schuurman, M.K. Schwartz, J. Szymanski, and A. Whiteley, 2023: Connecting research and practice to enhance the evolutionary potential of species under climate change. *Conservation Science and Practice*, **5** (2), e12855. https://doi.org/10.1111/csp2.12855

191. UNEP, 2019: Sand and Sustainability: Finding New Solutions for Environmental Governance of Global Sand Resources. United Nations Environment Programme. https://wedocs.unep.org/handle/20.500.11822/28163;jsessionid=333820b5a8c38cdd7f7f44fc1984d9ae

192. Grossman, E.E., A.W. Stevens, D. P, D. George, and D. Finlayson, 2020: Sediment export and impacts associated with river delta channelization compound estuary vulnerability to sea-level rise. *Marine Geology*, **430**, 106336. https://doi.org/10.1016/j.margeo.2020.106336

193. Knox, R.L., E.E. Wohl, and R.R. Morrison, 2022: Levees don't protect, they disconnect: A critical review of how artificial levees impact floodplain functions. *Science of The Total Environment*, **837**, 155773. https://doi.org/10.1016/j.scitotenv.2022.155773

194. Bond, M.H., T.G. Nodine, T.J. Beechie, and R.W. Zabel, 2019: Estimating the benefits of widespread floodplain reconnection for Columbia River Chinook salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, **76** (7), 1212–1226. https://doi.org/10.1139/cjfas-2018-0108

195. Grossman, E.E., S.C. Crosby, A.W. Stevens, D.J. Nowacki, N.R. vanAredonk, and C.A. Curran, 2022: Assessment of Vulnerabilities and Opportunities to Restore Marsh Sediment Supply at Nisqually River Delta, West-Central Washington. USGS Open-File Report 2022–1088. U.S. Geological Survey, 50 pp. https://doi.org/10.3133/ofr20221088

196. Moritsch, M.M., K.B. Byrd, M. Davis, A. Good, J.Z. Drexler, J.T. Morris, I. Woo, L. Windham-Myers, E. Grossman, G. Nakai, K.L. Poppe, and J.M. Rybczyk, 2022: Can coastal habitats rise to the challenge? Resilience of estuarine habitats, carbon accumulation, and economic value to sea-level rise in a Puget Sound estuary. *Estuaries and Coasts*, **45** (8), 2293–2309. https://doi.org/10.1007/s12237-022-01087-5

197. Copeland, T., B.J. Bowersox, M.W. Ackerman, and C. Camacho, 2019: Patterns of iteroparity in wild Snake River steelhead. *Transactions of the American Fisheries Society*, **148** (5), 926–937. https://doi.org/10.1002/tafs.10187

198. Morley, S.A., M.M. Foley, J.J. Duda, M.M. Beirne, R.L. Paradis, R.C. Johnson, M.L. McHenry, M. Elofson, E.M. Sampson, R.E. McCoy, J. Stapleton, and G.R. Pess, 2020: Shifting food web structure during dam removal—Disturbance and recovery during a major restoration action. *PLoS ONE*, **15** (9), e0239198. https://doi.org/10.1371/journal.pone.0239198

199. Penaluna, B.E., G.H. Reeves, Z.C. Barnett, P.A. Bisson, J.M. Buffington, C.A. Dolloff, R.L. Flitcroft, C.H. Luce, K.H. Nislow, J.D. Rothlisberger, and M.L. Warren Jr, 2018: Using natural disturbance and portfolio concepts to guide aquatic–riparian ecosystem management. *Fisheries*, **43** (9), 406–422. https://doi.org/10.1002/fsh.10097

200. Quinn, T.P., M.H. Bond, S.J. Brenkman, R. Paradis, and R.J. Peters, 2017: Re-awakening dormant life history variation: Stable isotopes indicate anadromy in bull trout following dam removal on the Elwha River, Washington. *Environmental Biology of Fishes*, **100** (12), 1659–1671. https://doi.org/10.1007/s10641-017-0676-0

201. Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Povak, and F.K. Lake, 2021: Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*, **31** (8), e02432. https://doi.org/10.1002/eap.2432

202. Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, R.E. Keane, L.N. Kobziar, C.A. Kolden, M. North, S.A. Parks, H.D. Safford, J.T. Stevens, L.L. Yocom, D.J. Churchill, R.W. Gray, D.W. Huffman, F.K. Lake, and P. Khatri-Chhetri, 2021: Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications*, **31** (8), e02433. https://doi.org/10.1002/eap.2433

203. Vose, J.M., D.L. Peterson, C.H. Luce, and T. Patel-Weynand, 2019: Effects of Drought on Forests and Rangelands in the United States: Translating Science into Management Responses. Gen. Tech. Rep. WO-98. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 227 pp. https://doi.org/10.2737/wo-gtr-98

204. Halofsky, J.E., D.L. Peterson, and H.R. Prendeville, 2018: Assessing vulnerabilities and adapting to climate change in northwestern U.S. forests. *Climatic Change*, **146** (1-2), 89–102. https://doi.org/10.1007/s10584-017-1972-6

205. Reilly, M.J., A. Zuspan, J.S. Halofsky, C. Raymond, A. McEvoy, A.W. Dye, D.C. Donato, J.B. Kim, B.E. Potter, N. Walker, R.J. Davis, C.J. Dunn, D.M. Bell, M.J. Gregory, J.D. Johnston, B.J. Harvey, J.E. Halofsky, and B.K. Kerns, 2022: Cascadia burning: The historic, but not historically unprecedented, 2020 wildfires in the Pacific Northwest, USA. *Ecosphere*, **13** (6), e4070. https://doi.org/10.1002/ecs2.4070

206. Endter-Wada, J., K.M. Kettenring, and A.E. Sutton-Grier, 2018: Sustaining wetlands to mitigate disasters and protect people. *Frontiers in Ecology and the Environment*, **16** (8), 431–431. https://doi.org/10.1002/fee.1959

207. WA State Department of Ecology, 2022: Mitigation Bank Projects. State of Washington, Department of Ecology. https://ecology.wa.gov/water-shorelines/wetlands/mitigation/wetland-mitigation-banking/mitigation-bank-projects

208. Van den Bosch, K. and J.W. Matthews, 2017: An assessment of long-term compliance with performance standards in compensatory mitigation wetlands. *Environmental Management*, **59** (4), 546–556. https://doi.org/10.1007/s00267-016-0804-1

209. Oja, E.B., L.K. Swartz, E. Muths, and B.R. Hossack, 2021: Amphibian population responses to mitigation: Relative importance of wetland age and design. *Ecological Indicators*, **131**, 108123. https://doi.org/10.1016/j.ecolind.2021.108123

210. Khanal, R., M.P. Brady, C.O. Stöckle, K. Rajagopalan, J. Yoder, and M.E. Barber, 2021: The economic and environmental benefits of partial leasing of agricultural water rights. *Water Resources Research*, **57** (11), e2021WR029712. https://doi.org/10.1029/2021wr029712

211. Leonard, B., C. Costello, and G.D. Libecap, 2019: Expanding water markets in the western United States: barriers and lessons from other natural resource markets. *Review of Environmental Economics and Policy*, **13** (1), 43–61. https://doi.org/10.1093/reep/rey014

212. Gienapp, P., C. Teplitsky, J.S. Alho, J.A. Mills, and J. Merilä, 2008: Climate change and evolution: Disentangling environmental and genetic responses. *Molecular Ecology*, **17** (1), 167–178. https://doi.org/10.1111/j.1365-294x.2007.03413.x

213. Merilä, J. and A.P. Hendry, 2014: Climate change, adaptation, and phenotypic plasticity: The problem and the evidence. *Evolutionary Applications*, **7** (1), 1–14. https://doi.org/10.1111/eva.12137

214. Bigelow, D.P. and A. Borchers, 2017: Major Uses of Land in the United States, 2012. EIB-178. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=84879

215. ERS, 2023: Data Files: U.S. and State-Level Farm Income and Wealth Statistics. U.S. Department of Agriculture, Economic Research Service, accessed March 20, 2023. https://www.ers.usda.gov/data-products/farm-income-and-wealth-statistics/data-files-u-s-and-state-level-farm-income-and-wealth-statistics/

216. Rajagopalan, K., K.J. Chinnayakanahalli, C.O. Stockle, R.L. Nelson, C.E. Kruger, M.P. Brady, K. Malek, S.T. Dinesh, M.E. Barber, A.F. Hamlet, G.G. Yorgey, and J.C. Adam, 2018: Impacts of near-term climate change on irrigation demands and crop yields in the Columbia River Basin. *Water Resources Research*, **54** (3), 2152–2182. https://doi.org/10.1002/2017wr020954

217. Noorazar, H., L. Kalcsits, V.P. Jones, M.S. Jones, and K. Rajagopalan, 2022: Climate change and chill accumulation: Implications for tree fruit production in cold-winter regions. *Climatic Change*, **171** (3), 34. https://doi.org/10.1007/s10584-022-03339-6

218. Willsea, N., V. Blanco, K. Rajagopalan, T. Campbell, O. Howe, and L. Kalcsits, 2023: Reviewing the tradeoffs between sunburn mitigation and red color development in apple under a changing climate. *Horticulturae*, **9** (4), 492. https://doi.org/10.3390/horticulturae9040492

219. Gallinat, A.S., R.B. Primack, and D.L. Wagner, 2015: Autumn, the neglected season in climate change research. *Trends in Ecology & Evolution*, **30** (3), 169–176. https://doi.org/10.1016/j.tree.2015.01.004

220. Rajagopalan, K., G. DeGrandi-Hoffman, M. Pruett, V.P. Jones, V. Corby-Harris, J. Pireaud, R. Curry, B. Hopkins, and T. Northfield, 2022: Changing Honey Bee Overwintering Dynamics Under Warmer Autumns and Winters Create New Risks for Pollination Services. Research Square. https://doi.org/10.21203/rs.3.rs-1394621/v1

221. Jones, G. and H. Schultz, 2016: Climate change and emerging cool climate wine regions. *Wine and Viticulture Journal*, **31** (6), 51–53. https://search.informit.org/doi/10.3316/informit.523901697092406

222. Mirabelli-Montan, Y.A., M. Marangon, A. Graça, C.M. Mayr Marangon, and K.L. Wilkinson, 2021: Techniques for mitigating the effects of smoke taint while maintaining quality in wine production: A review. *Molecules*, **26** (6), 1672. https://doi.org/10.3390/molecules26061672

223. Ansah, E.O. and O.S. Walsh, 2021: Impact of 2021 drought in the Pacific Northwest. *Crops & Soils*, **54** (6), 46–49. https://doi.org/10.1002/crso.20145

224. NASS, 2021: Small Grains 2021 Summary. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/todays_reports/reports/smgr0921.pdf

225. Winford, E. and K. Lee, 2021: Rangelands report. In: *Idaho Climate-Economy Impacts Assessment*. James A. and Louise McClure Center for Public Policy Research, University of Idaho, Boise, ID. https://www.uidaho.edu/president/direct-reports/mcclure-center/iceia/land

226. Chengot, R., J.W. Knox, and I.P. Holman, 2021: Evaluating the feasibility of water sharing as a drought risk management tool for irrigated agriculture. *Sustainability*, **13** (3). https://doi.org/10.3390/su13031456

227. Coppock, D.L., 2020: Improving drought preparedness among Utah cattle ranchers. *Rangeland Ecology & Management*, **73** (6), 879–890. https://doi.org/10.1016/j.rama.2020.08.003

228. Peck, D., J. Derner, W. Parton, M. Hartman, and B. Fuchs, 2019: Flexible stocking with Grass-Cast: A new grassland productivity forecast to translate climate outlooks for ranchers. *Western Economics Forum*, **17** (1), 24–39. https://doi.org/10.22004/ag.econ.287342

229. Diffenbaugh, N.S., F.V. Davenport, and M. Burke, 2021: Historical warming has increased U.S. crop insurance losses. *Environmental Research Letters*, **16** (8), 084025. https://doi.org/10.1088/1748-9326/ac1223

230. Reyes, J.J. and E. Elias, 2019: Spatio-temporal variation of crop loss in the United States from 2001 to 2016. *Environmental Research Letters*, **14** (7), 074017. https://doi.org/10.1088/1748-9326/ab1ac9

231. Malek, K., P. Reed, J. Adam, T. Karimi, and M. Brady, 2020: Water rights shape crop yield and revenue volatility tradeoffs for adaptation in snow dependent systems. *Nature Communications*, **11** (1), 3473. https://doi.org/10.1038/s41467-020-17219-z

232. Gaines, W.L., P.F. Hessburg, G.H. Aplet, P. Henson, S.J. Prichard, D.J. Churchill, G.M. Jones, D.J. Isaak, and C. Vynne, 2022: Climate change and forest management on federal lands in the Pacific Northwest, USA: Managing for dynamic landscapes. *Forest Ecology and Management*, **504**, 119794. https://doi.org/10.1016/j.foreco.2021.119794

233. Davis, K.T., P.E. Higuera, S.Z. Dobrowski, S.A. Parks, J.T. Abatzoglou, M.T. Rother, and T.T. Veblen, 2020: Fire-catalyzed vegetation shifts in ponderosa pine and Douglas-fir forests of the western United States. *Environmental Research Letters*, **15** (10), 1040b8. https://doi.org/10.1088/1748-9326/abb9df

234. Halofsky, J.E., D.L. Peterson, and R.A. Gravenmier, 2022: Climate Change Vulnerability and Adaptation in Southwest Oregon. Gen. Tech. Rep. PNW-GTR-995. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 445 pp. https://doi.org/10.2737/pnw-gtr-995

235. Hashida, Y. and D.J. Lewis, 2022: Estimating welfare impacts of climate change using a discrete-choice model of land management: An application to western U.S. forestry. *Resource and Energy Economics*, **68**, 101295. https://doi.org/10.1016/j.reseneeco.2022.101295

236. Restaino, C.M., D.L. Peterson, and J. Littell, 2016: Increased water deficit decreases Douglas fir growth throughout western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (34), 9557–9562. https://doi.org/10.1073/pnas.1602384113

237. Hudec, J.L., J.E. Halofsky, D.L. Peterson, and J.J. Ho, 2019: Climate Change Vulnerability and Adaptation in Southwest Washington. Gen. Tech. Rep. PNW-GTR-977. U.S. Department of Agriculture, Forest Service. Pacific Northwest Research Station, Portland, OR, 249 pp. https://doi.org/10.2737/pnw-gtr-977

238. Kerns, B.K., D.C. Powell, S. Mellmann-Brown, G. Carnwath, and J.B. Kim, 2018: Effects of projected climate change on vegetation in the Blue Mountains ecoregion, USA. *Climate Services*, **10**, 33–43. https://doi.org/10.1016/j.cliser.2017.07.002

239. Hicke, J.A., A.J.H. Meddens, and C.A. Kolden, 2016: Recent tree mortality in the western United States from bark beetles and forest fires. *Forest Science*, **62** (2), 141–153. https://doi.org/10.5849/forsci.15-086

240. Morgan, P., E.K. Heyerdahl, E.K. Strand, S.C. Bunting, J.P. Riser Ii, J.T. Abatzoglou, M. Nielsen-Pincus, and M. Johnson, 2020: Fire and land cover change in the Palouse Prairie–forest ecotone, Washington and Idaho, USA. *Fire Ecology*, **16** (1), 2. https://doi.org/10.1186/s42408-019-0061-9

241. Paveglio, T.B., C. Moseley, M.S. Carroll, D.R. Williams, E.J. Davis, and A.P. Fischer, 2015: Categorizing the social context of the wildland urban interface: Adaptive capacity for wildfire and community "archetypes". *Forest Science*, **61** (2), 298–310. https://doi.org/10.5849/forsci.14-036

242. Hashida, Y. and D.J. Lewis, 2019: The intersection between climate adaptation, mitigation, and natural resources: An empirical analysis of forest management. *Journal of the Association of Environmental and Resource Economists*, **6** (5), 893–926. https://doi.org/10.1086/704517

243. Scouse, A., S.S. Kelley, S. Liang, and R. Bergman, 2020: Regional and net economic impacts of high-rise mass timber construction in Oregon. *Sustainabile Cities and Society*, **61**, 102154. https://doi.org/10.1016/j.scs.2020.102154.

244. Law, B.E., T.W. Hudiburg, L.T. Berner, J.J. Kent, P.C. Buotte, and M.E. Harmon, 2018: Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (14), 3663–3668. https://doi.org/10.1073/pnas.1720064115

245. Mucioki, M., J. Sowerwine, D. Sarna-Wojcicki, F.K. Lake, and S. Bourque, 2021: Conceptualizing Indigenous Cultural Ecosystem Services (ICES) and benefits under changing climate conditions in the Klamath River Basin and their implications for land management and governance. *Journal of Ethnobiology*, **41** (3), 313–330. https://doi.org/10.2993/0278-0771-41.3.313

246. WA DNR, 2020: Summary of Natural and Working Lands Carbon Inventories and Incentive Programs in Washington. Washington Department of Natural Resources. https://app.leg.wa.gov/reportstothelegislature/home/getpdf?filename=dnr%20carbon%20sequestration%20report_8f19b00b-5acf-4c97-83b4-16cecb559803.pdf

247. Bellquist, L., V. Saccomanno, B.X. Semmens, M. Gleason, and J. Wilson, 2021: The rise in climate change-induced federal fishery disasters in the United States. *PeerJ*, **9**, e11186. https://doi.org/10.7717/peerj.11186

248. Cramer, L.A., C. Flathers, D. Caracciolo, S.M. Russell, and F. Conway, 2018: Graying of the fleet: Perceived impacts on coastal resilience and local policy. *Marine Policy*, **96**, 27–35. https://doi.org/10.1016/j.marpol.2018.07.012

249. Haugen, B.I., L.A. Cramer, G.G. Waldbusser, and F.D.L. Conway, 2021: Resilience and adaptive capacity of Oregon's fishing community: Cumulative impacts of climate change and the graying of the fleet. *Marine Policy*, **126**, 104424. https://doi.org/10.1016/j.marpol.2021.104424

250. Ritzman, J., A. Brodbeck, S. Brostrom, S. McGrew, S. Dreyer, T. Klinger, and S.K. Moore, 2018: Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 U.S. West Coast harmful algal bloom. *Harmful Algae*, **80**, 35–45. https://doi.org/10.1016/j.hal.2018.09.002

251. Chang, M., H. Kennard, L. Nelson, K. Wrubel, S. Gagnon, R. Monette, and J. Ledford, 2020: Makah traditional knowledge and cultural resource assessment: A preliminary framework to utilize traditional knowledge in climate change planning. *Parks Stewardship Forum*, **36** (1). https://doi.org/10.5070/p536146381

252. Schlinger, C., O. Conroy-Ben, C. Cooley, N. Cooley, M. Cruz, D. Dotson, J. Doyle, M.J. Eggers, P. Hardison, M. Hatch, C. Hogue, K. Jacobson Hedin, C. Jones, K. Lanphier, D. Marks-Marino, D. Mosley, F. Olsen Jr., and M. Peacock, 2021: Ch. 4.2. Water. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, Flagstaff, AZ, 98–141. http://nau.edu/stacc2021

253. NWIFC, 2016: Climate Change and Our Natural Resources: A Report from the Treaty Tribes in Western Washington. Northwest Indian Fisheries Commission. https://nwifc.org/w/wp-content/uploads/downloads/2017/01/CC_and_Our_NR_Report_2016-1.pdf

254. Mojica, J., K. Cousins, and T. Madsen, 2021: Economic Analysis of Outdoor Recreation in Oregon. Earth Economics, Tacoma, WA. https://static1.squarespace.com/static/561dcdc6e4b039470e9afc00/t/5ffe3084ce56a6552b7a3c71/1610494115376/EconomicAnalysisofOutdoorRecreationinOregon_OTC-EarthEconomics_SmallRes.pdf

255. Snover, A.K., N.J. Mantua, J.S. Littell, M.A. Alexander, M.M. McClure, and J. Nye, 2013: Choosing and using climate change scenarios for ecological-impact assessments and conservation decisions. *Conservation Biology*, **27** (6), 1147–1157. https://doi.org/10.1111/cobi.12163

256. Maas, A. and K.E. Himes, 2021: Recreation and tourism report. In: *Idaho Climate-Economy Impacts Assessment*. James A. & Louise McClure Center for Public Policy Research, University of Idaho, Boise, ID. https://www.uidaho.edu/president/direct-reports/mcclure-center/iceia/recreation-and-tourism

257. Wlostowski, A.N., K.S. Jennings, R.E. Bash, J. Burkhardt, C.W. Wobus, and G. Aggett, 2021: Dry landscapes and parched economies: A review of how drought impacts nonagricultural socioeconomic sectors in the US Intermountain West. *WIREs Water*, **9** (1). https://doi.org/10.1002/wat2.1571

258. Tohver, I.M., A.F. Hamlet, and S.-Y. Lee, 2014: Impacts of 21st-century climate change on hydrologic extremes in the Pacific Northwest region of North America. *Journal of the American Water Resources Association*, **50** (6), 1461–1476. https://doi.org/10.1111/jawr.12199

259. Musselman, K.N., F. Lehner, K. Ikeda, M.P. Clark, A.F. Prein, C. Liu, M. Barlage, and R. Rasmussen, 2018: Projected increases and shifts in rain-on-snow flood risk over western North America. *Nature Climate Change*, **8** (9), 808–812. https://doi.org/10.1038/s41558-018-0236-4

260. Kim, M.-K. and P.M. Jakus, 2019: Wildfire, national park visitation, and changes in regional economic activity. *Journal of Outdoor Recreation and Tourism*, **26**, 34–42. https://doi.org/10.1016/j.jort.2019.03.007

261. Peterson, D.L., M.S. Hand, J.J. Ho, and S.K. Dante-Wood, 2022: Ch. 7. Climate change effects on outdoor recreation in Southwest Oregon. In: *Climate Change Vulnerability and Adaptation in Southwest Oregon*. Halofsky, J.E., Peterson D.L., and R.A. Gravenmier, Eds. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, OR, 361–398. https://www.fs.usda.gov/pnw/pubs/pnw-gtr995.pdf

262. Chan, N.W. and C.J. Wichman, 2020: Climate change and recreation: Evidence from North American cycling. *Environmental and Resource Economics*, **76** (1), 119–151. https://doi.org/10.1007/s10640-020-00420-5

263. Hjerpe, E., A. Hussain, and T. Holmes, 2020: Amenity migration and public lands: Rise of the protected areas. *Environmental Management*, **66** (1), 56–71. https://doi.org/10.1007/s00267-020-01293-6

264. NRDC, 2019: Climate Change and Health in Washington. IB: 19-09-B. National Research Defense Council, 11 pp. https://www.nrdc.org/sites/default/files/climate-change-health-impacts-washington-ib.pdf

265. Whyte, K., C. Avery, E. Azzuz, J. Breckinridge, C. Cooley, K. Cozzetto, R. Croll, M. Cruz, P. Ezcurra, P. Hardison, C. Jones, F. Lake, C. Magee, D.M. Marks-Marino, D., H. Mullen, C. Nelson, A. Pairis, H. Panci, B. Rodriguez, H. Sorensen, C. Spriggs, and A. Warneke, 2021: Ch. 4. Ecosystems & biodiversity. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 56–80. http://nau.edu/stacc2021

266. NIFA, 2021: Improving the Ecological Services of Nez Perce Lands Through Agriculture Management and Decision Support Tools. U.S. Department of Agriculture, National Institue of Food and Agriculture. https://portal.nifa.usda.gov/web/crisprojectpages/1024991-improving-the-ecological-services-of-nez-perce-lands-through-agriculture-management-and-decision-support-tools.html

267. King, A., 2021: Yakama Nation seeks food sovereignty in new farming venture with weighty history. *Oregon Public Broadcasting*, December 13, 2021. https://www.opb.org/article/2021/12/12/yakama-nation-food-sovereignty-farming-venture/

268. Yakama Nation, 2019: Climate Action Plan for the Territories of the Yakama Nation. Yakama Nation. https://mrsc.org/getmedia/7e788879-99dd-4711-9cc8-c6cacefe6cd4/m58totyncap.pdf.aspx

269. Matsumoto, S., 2022: Environmental justice for food system workers: Heat-illness prevention standards as one step toward just transition. *Pace Environmental Law Review*, **40** (1). https://ssrn.com/abstract=4338860

270. Henry, M.S., M.D. Bazilian, and C. Markuson, 2020: Just transitions: Histories and futures in a post-COVID world. *Energy Research & Social Science*, **68**, 101668. https://doi.org/10.1016/j.erss.2020.101668

271. Roemer, K.F. and J.H. Haggerty, 2021: Coal communities and the U.S. energy transition: A policy corridors assessment. *Energy Policy*, **151**, 112112. https://doi.org/10.1016/j.enpol.2020.112112

272. Proctor, K.W., G.S. Murthy, and C.W. Higgins, 2021: Agrivoltaics align with Green New Deal goals while supporting investment in the US' rural economy. *Sustainability*, **13** (1), 137. https://doi.org/10.3390/su13010137

273. Shortridge, J. and J.S. Camp, 2019: Addressing climate change as an emerging risk to infrastructure systems. *Risk Analysis*, **39** (5), 959–967. https://doi.org/10.1111/risa.13234

274. Araújo, K., 2022: Ch. 1. The evolving field of energy transitions. In: *Routledge Handbook of Energy Transitions*. Araújo, K., Ed. Taylor & Francis, London, UK, 17. https://doi.org/10.4324/9781003183020

275. Araújo, K. and D. Shropshire, 2021: A meta-level framework for evaluating resilience in net-zero carbon power systems with extreme weather events in the United States. *Energies*, **14** (14), 4243. https://doi.org/10.3390/en14144243.

276. Guidotti, R., H. Chmielewski, V.U. Unnikrishnan, P. Gardoni, T. McAllister, and J.W. Lindt, 2016: Modeling the resilience of critical infrastructure: The role of network dependencies. *Sustainable and Resilient Infrastructure*, **1** (3–4), 153–168. https://doi.org/10.1080/23789689.2016.1254999

277. Bumbaco, K.A., M.H. Rogers, L.W. O'Neill, D.J. Hoekema, and C.L. Raymond, 2022: 2021 Pacific Northwest Water Year Impacts Assessment. Office of the Washington State Climatologist, Climate Impacts Group, Oregon State Climatologist, Idaho Department of Water Resources, and the National Oceanic and Atmospheric Administration's National Integrated Drought Information System. https://www.drought.gov/documents/2021-pacific-northwest-water-year-impacts-assessment

278. Bumbaco, K.A., C.L. Raymond, L.W. O'Neill, A. Mehta, and D.J. Hoekema, 2023: 2022 Pacific Northwest Water Year Impacts Assessment. Office of the Washington State Climatologist, Climate Impacts Group, Oregon State Climatologist, Idaho Department of Water Resources, and the National Oceanic and Atmospheric Administration's National Integrated Drought Information System. https://www.drought.gov/documents/2022-pacific-northwest-water-year-impacts-assessment

279. Bumbaco, K.A., C.L. Raymond, L.W. O'Neill, and D.J. Hoekema, 2021: 2020 Pacific Northwest Water Year Impacts Assessment. Office of the Washington State Climatologist, Climate Impacts Group, Oregon State Climatologist, Idaho Department of Water Resources, and the National Oceanic and Atmospheric Administration's National Integrated Drought Information System. https://cig.uw.edu/publications/2020-pacific-northwest-water-year-impacts-assessment/

280. U.S. Census Bureau, 1990: Historical Census of Housing Tables: Sewage Disposal. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/tables/time-series/dec/coh-sewage.html

281. Cox, A.H., D. Surabian, G.W. Loomis, J.D. Turenne, and J.A. Amador, 2020: Temporal variability in the vertical separation distance of septic system drainfields along the southern Rhode Island coast. *Water, Air, & Soil Pollution*, **231** (3), 107. https://doi.org/10.1007/s11270-020-04488-z

282. Kohler, L.E., J. Silverstein, and B. Rajagopalan, 2016: Modeling on-site wastewater treatment system performance fragility to hydroclimate stressors. *Water Science and Technology*, **74** (12), 2917–2926. https://doi.org/10.2166/wst.2016.467

283. Hoghooghi, N., J.S. Pippin, B.K. Meyer, J.B. Hodges, and B.P. Bledsoe, 2021: Frontiers in assessing septic systems vulnerability in coastal Georgia, USA: Modeling approach and management implications. *PLoS ONE*, **16** (8), e0256606. https://doi.org/10.1371/journal.pone.0256606

284. Devereux, R., Y. Wan, J.L. Rackley, V. Fasselt, and D.N. Vivian, 2021: Comparative analysis of nitrogen concentrations and sources within a coastal urban bayou watershed: A multi-tracer approach. *Science of The Total Environment*, **776**, 145862. https://doi.org/10.1016/j.scitotenv.2021.145862

285. Mauger, G.S. and J.S. Won, 2019: Expanding the Ensemble of Precipitation Projections for King County. University of Washington, Climate Impacts Group, Seattle, WA. https://cig.uw.edu/publications/expanding-the-ensemble-of-precipitation-projections-for-king-county/

286. Morgan, H., G. Mauger, J. Won, and D. Gould, 2021: Projected Changes in Extreme Precipitation Web Tool. University of Washington Climate Impacts Group. https://doi.org/10.6069/79cv-4233

287. Salathé Jr., E.P., A.F. Hamlet, C.F. Mass, S.-Y. Lee, M. Stumbaugh, and R. Steed, 2014: Estimates of twenty-first-century flood risk in the Pacific Northwest based on regional climate model simulations. *Journal of Hydrometeorology*, **15** (5), 1881–1899. https://doi.org/10.1175/jhm-d-13-0137.1

288. Van Abs, D.J., 2016: Climate Change Adaptation in the Water Supply Sector. Rutgers, The State University of New Jersey. https://njadapt.rutgers.edu/docman-lister/conference-materials/166-climate-change-adaptation-in-water-supply-sector-final-1/file

289. EIA, n.d.: U.S. State Profiles and Energy Estimates. U.S. Energy Information Administration. https://www.eia.gov/state/

290. Turner, S.W., N. Voisin, K.D. Nelson, and V.C. Tidwell, 2022: Drought Impacts on Hydroelectric Power Generation in the Western United States: A Multiregional Analysis of 21st Century Hydropower Generation. PNNL-33212. U.S. Department of Energy, Pacific Northwest National Laboratory, Richland, WA. https://doi.org/10.2172/1887470

291. Voisin, N., A. Dyreson, T. Fu, M. O'Connell, S.W.D. Turner, T. Zhou, and J. Macknick, 2020: Impact of climate change on water availability and its propagation through the western U.S. power grid. *Applied Energy*, **276**, 115467. https://doi.org/10.1016/j.apenergy.2020.115467

292. Pitcock, B., T. Lazarte, and C. Christen, 2020: Lower Snake River Hydropower Dams: A Resilience Assessment of Regional Impacts with Proposed Dam Removal. Boise State University, 19 pp. https://wpwww-prod.s3.us-west-2.amazonaws.com/uploads/sites/151/2020/05/Resilience-with-Dams.pdf

293. Hall, S.M., 2021: Energy report. In: *Idaho Climate-Economy Impacts Assessment*. James A. & Louise McClure Center for Public Policy Research, University of Idaho, Boise, ID. https://www.uidaho.edu/president/direct-reports/mcclure-center/iceia

294. Turner, S.W.D., N. Voisin, J. Fazio, D. Hua, and M. Jourabchi, 2019: Compound climate events transform electrical power shortfall risk in the Pacific Northwest. *Nature Communications*, **10** (1), 8. https://doi.org/10.1038/s41467-018-07894-4

295. Cederholm, C.J., D.H. Johnson, R.E. Bilby, L.G. Dominguez, A.M. Garrett, W.H. Graeber, E.L. Greda, M.D. Kunze, B.G. Marcot, J.F. Palmisano, R.W. Plotnikoff, W.G. Pearcy, C.A. Simenstad, and P.C. Trotter, 2000: Pacific Salmon and Wildlife—Ecological Contexts, Relationships, and Implications for Management. Special Edition Technical Report. Washington Department of Fish and Wildlife, Olympia, WA. https://wdfw.wa.gov/publications/00063

296. Yoder, J., C. Raymond, R. Basu, S. Deol, A. Fremier, K. Garcia, G. Mauger, J. Padowski, M. Rogers, and A. Stahl, 2022: Climate Change and Stream Flow: Barriers and Opportunities. Preliminary project report to the Washington State Department of Ecology. Washington State, Department of Ecology, Water Resources Program, Olympia, WA. https://apps.ecology.wa.gov/publications/documents/2211029.pdf

297. Nez Perce Tribe, 2022: *Nimiipuu Energy May 2022*. Nez Perce Tribe. https://vimeo.com/710582042

298. EPI, 2023: Wildfire-Grid Risk, Power Talk. Boise State University, Energy Policy Institute. https://www.boisestate.edu/epi/upcomingevents/

299. Utility Wildland Fire Prevention Advisory Committee—Duties—Report—Membership—Immunity. RCW 76.04.780, Washington State Legislature, 2022. https://app.leg.wa.gov/rcw/default.aspx?cite=76.04.780

300. Araújo, K.M., T.J. Foxon, J. Markard, R. Raven, and R. Schaeffer, 2022: Ch. 29. Reconceptualizing the next frontier in energy transitions. In: *Routledge Handbook of Energy Transitions*. Araújo, K.M., Ed. Taylor & Francis, London, UK, 6. https://doi.org/10.4324/9781003183020-34

301. Black, G., D. Shropshire, and K. Araújo, 2021: Ch. 22. Small modular reactor (SMR) adoption: Opportunities and challenges for emerging markets. In: *Handbook of Small Modular Nuclear Reactors*, 2nd ed. Ingersoll, D.T. and M.D. Carelli, Eds. Woodhead Publishing, 557–593. https://doi.org/10.1016/b978-0-12-823916-2.00022-9

302. Araújo, K.M., 2018: *Low Carbon Energy Transitions: Turning Points in National Policy and Innovation*. Oxford University Press. https://doi.org/10.1093/oso/9780199362554.001.0001

303. Idaho Power, 2021: Integrated Resource Plan. Idaho Power. https://docs.idahopower.com/pdfs/aboutus/planningforfuture/irp/2021/2021%20irp_web.pdf

304. Araújo, K., D. Mahajan, R. Kerr, and M. da Silva, 2017: Global biofuels at the crossroads: An overview of technical, policy, and investment complexities in the sustainability of biofuel development. *Agriculture*, **7** (4). https://doi.org/10.3390/agriculture7040032

305. Aumeier, S.E., D.E. Shropshire, T. Allen, K. Araújo, C. Bell, M. Craig, J. Parsons, and T. Righetti, 2021: Emerging Energy Market Analysis Initiative, Methodological Framework. INL/EXT-21-65347. U.S. Department of Energy, Idaho National Laboratory, Idaho Falls, ID. https://doi.org/10.2172/1838119

306. Shropshire, D.E., K. Araujo, C. Koerner, C. Bell, R. Johnson, J. Parsons, S. Gerace, E. Holubynak, T. Righetti, and S.E. Aumeier, 2023: Microreactor Applications in U.S. Markets, Evaluation of State-Level Legal, Regulatory, Economic and Technology Implications. INL/RPT-23-71733. U.S. Department of Energy, Idaho National Laboratory, Idaho Falls, ID. https://doi.org/10.2172/1964093

307. Ellingwood, B.R., H. Cutler, P. Gardoni, W.G. Peacock, J.W. van de Lindt, and N. Wang, 2016: The Centerville virtual community: A fully integrated decision model of interacting physical and social infrastructure systems. *Sustainable and Resilient Infrastructure*, **1** (3-4), 95–107. https://doi.org/10.1080/23789689.2016.1255000

308. Markolf, S.A., C. Hoehne, A. Fraser, M.V. Chester, and B.S. Underwood, 2019: Transportation resilience to climate change and extreme weather events—Beyond risk and robustness. *Transport Policy*, **74**, 174–186. https://doi.org/10.1016/j.tranpol.2018.11.003

309. Dye, A.W., J.B. Kim, A. McEvoy, F. Fang, and K.L. Riley, 2021: Evaluating rural Pacific Northwest towns for wildfire evacuation vulnerability. *Natural Hazards*, **107** (1), 911–935. https://doi.org/10.1007/s11069-021-04615-x

310. Rodrigue, J.-P., 2020: *The Geography of Transport Systems*, 5th ed. Routledge, London, UK, 480 pp. https://doi.org/10.4324/9780429346323

311. Rempel, A. and M. Babbar-Sebens, 2021: Built environment. In: *Fifth Oregon Climate Assessment*. Oregon Climate Change Research Institute, Oregon State University, Corvallis, OR, 113–136. https://ir.library.oregonstate.edu/concern/technical_reports/pz50h457p

312. Oregon DOT, 2014: Climate Change Vulnerability Assessment and Adaptation Options Study. Oregon Department of Transportation. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/oregon/final_report/odotreport.pdf

313. WSDOT, 2011: Climate Impacts Vulnerability Assessment. Washington State, Department of Transportation. https://wsdot.wa.gov/sites/default/files/2021-10/Climate-Impact-AssessmentforFHWA-12-2011.pdf

314. Faria, R., P. Marques, P. Moura, F. Freire, J. Delgado, and A.T. de Almeida, 2013: Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. *Renewable and Sustainable Energy Reviews*, **24**, 271–287. https://doi.org/10.1016/j.rser.2013.03.063

315. Hawkins, T.R., B. Singh, G. Majeau-Bettez, and A.H. Strømman, 2013: Comparative environmental life cycle assessment of conventional and electric vehicles. *Journal of Industrial Ecology*, **17** (1), 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x

316. Peng, T., X. Ou, and X. Yan, 2018: Development and application of an electric vehicles life-cycle energy consumption and greenhouse gas emissions analysis model. *Chemical Engineering Research and Design*, **131**, 699–708. https://doi.org/10.1016/j.cherd.2017.12.018

317. Gober, P., A. Middel, A. Brazel, S. Myint, H. Chang, J.D. Duh, and L. House-Peters, 2012: Tradeoffs between water conservation and temperature amelioration in Phoenix and Portland: Implications for urban sustainability. *Urban Geography*, **33** (7), 1030–1054. https://doi.org/10.2747/0272-3638.33.7.1030

318. Kramer, H.A., M.H. Mockrin, P.M. Alexandre, and V.C. Radeloff, 2019: High wildfire damage in interface communities in California. *International Journal of Wildand Fire*, **28** (9), 641–650. https://doi.org/10.1071/wf18108

319. May, N.W., C. Dixon, and D.A. Jaffe, 2021: Impact of wildfire smoke events on indoor air quality and evaluation of a low-cost filtration method. *Aerosol and Air Quality Research*, **21** (7), 210046. https://doi.org/10.4209/aaqr.210046

320. Stauffer, D.A., D.A. Autenrieth, J.F. Hart, and S. Capoccia, 2020: Control of wildfire-sourced $PM_{2.5}$ in an office setting using a commercially available portable air cleaner. *Journal of Occupational and Environmental Hygiene*, **17** (4), 109–120. https://doi.org/10.1080/15459624.2020.1722314

321. Liu, J.C., L.J. Mickley, M.P. Sulprizio, F. Dominici, X. Yue, K. Ebisu, G.B. Anderson, R.F.A. Khan, M.A. Bravo, and M.L. Bell, 2016: Particulate air pollution from wildfires in the Western US under climate change. *Climatic Change*, **138** (3), 655–666. https://doi.org/10.1007/s10584-016-1762-6

322. Liu, Y., E. Austin, J. Xiang, T. Gould, T. Larson, and E. Seto, 2021: Health impact assessment of the 2020 Washington state wildfire smoke episode: Excess health burden attributable to increased $PM_{2.5}$ exposures and potential exposure reductions. *GeoHealth*, **5** (5), e2020GH000359. https://doi.org/10.1029/2020gh000359

323. Durairajan, R., C. Barford, and P. Barford, 2018: Lights out: Climate change risk to Internet infrastructure. *Proceedings of the Applied Networking Research Workshop*, Montreal, QC, Canada. Association for Computing Machinery, 9–15. https://doi.org/10.1145/3232755.3232775

324. Adams-Schoen, S.J. and M. Smith, 2023: Land-use law and climate change. In: *Sixth Oregon Climate Assessment*. Fleishman, E., Ed. Oregon State University, Oregon Climate Change Research Institute, Corvallis, OR. https://doi.org/10.5399/osu/1161

325. Adams-Schoen, S.J., 2018: Beyond localism: Harnessing state adaptation lawmaking to facilitate local climate resilience. *Michigan Journal of Environmental & Administrative Law*, **8** (1). https://repository.law.umich.edu/mjeal/vol8/iss1/5

326. Grannis, J., J. Wyman, M. Singer, and J. Shoaf, 2012: Coastal management in the face of rising seas: Legal strategies for Connecticut. *Sea Grant Law and Policy Journal*, **5** (1), 59–88. https://www.georgetownclimate.org/reports/coastal-management-in-the-face-of-rising-seas-legal-strategies-for-connecticut.html

327. Siders, A., 2013: Managed Coastal Retreat: A Legal Handbook on Shifting Development away from Vulnerable Areas. Columbia Public Law Research Paper No. 14-365. Columbia University. https://doi.org/10.2139/ssrn.2349461

328. Bumbaco, K.A., K.D. Dello, and N.A. Bond, 2013: History of Pacific Northwest heat waves: Synoptic pattern and trends. *Journal of Applied Meteorology and Climatology*, **52** (7), 1618–1631. https://doi.org/10.1175/jamc-d-12-094.1

329. NWS, 2021: Weather Related Fatality and Injury Statistics. National Oceanic and Atmospheric Administration, National Weather Service. https://www.weather.gov/hazstat/

330. Silberner, J., 2021: Heat wave causes hundreds of deaths and hospitalisations in Pacific Northwest. *British Medical Journal*, **374**. https://doi.org/10.1136/bmj.n1696

331. Philip, S.Y., S.F. Kew, G.J. van Oldenborgh, F.S. Anslow, S.I. Seneviratne, R. Vautard, D. Coumou, K.L. Ebi, J. Arrighi, R. Singh, M. van Aalst, C. Pereira Marghidan, M. Wehner, W. Yang, S. Li, D.L. Schumacher, M. Hauser, R. Bonnet, L.N. Luu, F. Lehner, N. Gillett, J. Tradowsky, G.A. Vecchi, C. Rodell, R.B. Stull, R. Howard, and F.E.L. Otto, 2021: Rapid attribution analysis of the extraordinary heat wave on the Pacific coast of the US and Canada in June 2021. *Earth System Dynamics*, **13** (4), 1689–1713. https://doi.org/10.5194/esd-13-1689-2022

332. Zhang, X., T. Zhou, W. Zhang, L. Ren, J. Jiang, S. Hu, M. Zuo, L. Zhang, and W. Man, 2023: Increased impact of heat domes on 2021-like heat extremes in North America under global warming. *Nature Communications*, **14** (1), 1690. https://doi.org/10.1038/s41467-023-37309-y

333. Thompson, V., A.T. Kennedy-Asser, E. Vosper, Y.T.E. Lo, C. Huntingford, O. Andrews, M. Collins, G.C. Hegerl, and D. Mitchell, 2022: The 2021 western North America heat wave among the most extreme events ever recorded globally. *Science Advances*, **8** (18), 6860. https://doi.org/10.1126/sciadv.abm6860

334. Isaksen, T.B., M. Yost, E. Hom, and R. Fenske, 2014: Projected health impacts of heat events in Washington State associated with climate change. *Reviews on Environmental Health*, **29** (1-2), 119–123. https://doi.org/10.1515/reveh-2014-0029

335. Schramm, P.J., A. Vaidyanathan, L. Radhakrishnan, A. Gates, K. Hartnett, and P. Breysse, 2021: Heat-related emergency department visits during the Northwestern heat wave—United States. *Morbidity and Mortality Weekly Report*, **70**, 1020–1021. https://doi.org/10.15585/mmwr.mm7029e1

336. Stowell, J.D., C.-E. Yang, J.S. Fu, N.C. Scovronick, M.J. Strickland, and Y. Liu, 2022: Asthma exacerbation due to climate change-induced wildfire smoke in the western US. *Environmental Research Letters*, **17** (1), 014023. https://doi.org/10.1088/1748-9326/ac4138

337. Zhou, X., K. Josey, L. Kamareddine, M.C. Caine, T. Liu, L.J. Mickley, M. Cooper, and F. Dominici, 2021: Excess of COVID-19 cases and deaths due to fine particulate matter exposure during the 2020 wildfires in the United States. *Science Advances*, **7** (33), 8789. https://doi.org/10.1126/sciadv.abi8789

338. Kochi, I., G.H. Donovan, P.A. Champ, and J.B. Loomis, 2010: The economic cost of adverse health effects from wildfire-smoke exposure: A review. *International Journal of Wildland Fire*, **19** (7), 803–817. https://doi.org/10.1071/wf09077

339. McDermot, D. and M. Kadlec, 2022: Increased Medical and Emergency Department Claims for Asthma Following Wildfire Smoke Exposure in Washington State, 2014–2018. Washington State Health Services Research Project Research Brief No. 104. Washington State Office of Financial Management. https://ofm.wa.gov/sites/default/files/public/dataresearch/researchbriefs/brief104.pdf

340. Gasparrini, A., Y. Guo, M. Hashizume, E. Lavigne, A. Zanobetti, J. Schwartz, and A. Tobias, 2015: Mortality risk attributable to high and low ambient temperature: A multicountry observational study. *The Lancet*, **386** (9991), 369–375. https://doi.org/10.1016/s0140-6736(14)62114-0

341. Clayton, S., C. Manning, K. Krygsman, and M. Speiser, 2017: Mental Health and Our Changing Climate: Impacts, Implications, and Guidance. American Psychological Association and ecoAmerica, Washington, DC. https://www.apa.org/news/press/releases/2017/03/mental-health-climate.pdf

342. Pacheco, S.E., 2020: Catastrophic effects of climate change on children's health start before birth. *The Journal of Clinical Investigation*, **130** (2), 562–564. https://doi.org/10.1172/jci135005

343. Korsiak, J., L. Pinault, T. Christidis, R.T. Burnett, M. Abrahamowicz, and S. Weichenthal, 2022: Long-term exposure to wildfires and cancer incidence in Canada: A population-based observational cohort study. *The Lancet Planetary Health*, **6** (5), e400–e409. https://doi.org/10.1016/s2542-5196(22)00067-5

344. Belova, A., C.A. Gould, K. Munson, M. Howell, C. Trevisan, N. Obradovich, and J. Martinich, 2022: Projecting the suicide burden of climate change in the United States. *GeoHealth*, **6** (5), e2021GH000580. https://doi.org/10.1029/2021gh000580

345. Cianconi, P., S. Betrò, and L. Janiri, 2020: The impact of climate change on mental health: A systematic descriptive review. *Frontiers in Psychiatry*, **11**, 74. https://doi.org/10.3389/fpsyt.2020.00074

346. Jones, R.T., D.P. Ribbe, P. Cunningham, and J.D. Weddle, 2003: Psychosocial correlates of wildfire disaster: Post disaster adult reactions. *Fire Technology*, **39** (2), 103–117. https://doi.org/10.1023/a:1024229812303

347. Ursano, R.J., J.C. Morganstein, and R. Cooper, 2017: APA Resource Document: Resource Document on Mental Health and Climate Change. American Psychological Association. https://www.psychiatry.org/file%20library/psychiatrists/directories/library-and-archive/resource_documents/2017-resource-document-mental-health-climate-change.pdf

348. WHO, 2013: *Mental Health Action Plan 2013-2020*. World Health Organization, Geneva, Switzerland. https://www.who.int/publications/i/item/9789241506021

349. Mental Health America, 2020: Ranking the States. Mental Health America. https://mhanational.org/sites/default/files/State%20of%20Mental%20Health%20in%20America%20-%202020_0.pdf

350. Cerveny, L.K. and J.W. Baur, 2020: Homelessness and nonrecreational camping on national forests and grasslands in the United States: Law enforcement perspectives and regional trends. *Journal of Forestry*, **118** (2), 139–153. https://doi.org/10.1093/jofore/fvz065

351. Goldman, L., 2022: *Climate Change and Youth: Turning Grief and Anxiety into Activism*, 1st ed. Taylor & Francis, New York, 352 pp. https://doi.org/10.4324/9781003051770

352. Vickery, J. and L.M. Hunter, 2016: Native Americans: Where in environmental justice research? *Society & Natural Resources*, **29** (1), 36–52. https://doi.org/10.1080/08941920.2015.1045644

353. Anderson, C.A., 2001: Heat and violence. *Current Directions in Psychological Science*, **10** (1), 33–38. https://doi.org/10.1111/1467-8721.00109

354. Enenkel, M., L. See, R. Bonifacio, V. Boken, N. Chaney, P. Vinck, L. You, E. Dutra, and M. Anderson, 2015: Drought and food security—Improving decision-support via new technologies and innovative collaboration. *Global Food Security*, **4**, 51–55. https://doi.org/10.1016/j.gfs.2014.08.005

355. Friel, S., H. Berry, H. Dinh, L. O'Brien, and H.L. Walls, 2014: The impact of drought on the association between food security and mental health in a nationally representative Australian sample. *BMC Public Health*, **14** (1), 1102. https://doi.org/10.1186/1471-2458-14-1102

356. Hetherington, E., S. McDonald, M. Wu, and S. Tough, 2018: Risk and protective factors for mental health and community cohesion after the 2013 Calgary flood. *Disaster Medicine and Public Health Preparedness*, **12** (4), 470–477. https://doi.org/10.1017/dmp.2017.91

357. Stanke, C., V. Murray, R. Amlôt, J. Nurse, and R. Williams, 2012: The effects of flooding on mental health: Outcomes and recommendations from a review of the literature. *PLoS Currents*, **4**. https://doi.org/10.1371/4f9f1fa9c3cae

358. Hearst, M.O., J. Yang, S. Friedrichsen, K. Lenk, C. Caspi, and M.N. Laska, 2021: The availability of culturally preferred fruits, vegetables and whole grains in corner stores and non-traditional food stores. *International Journal of Environmental Research and Public Health*, **18** (9), 5030. https://doi.org/10.3390/ijerph18095030

359. Patchell, B. and K. Edwards, 2014: The role of traditional foods in diabetes prevention and management among Native Americans. *Current Nutrition Reports*, **3** (4), 340–344. https://doi.org/10.1007/s13668-014-0102-6

360. Sarkar, D., J. Walker-Swaney, and K. Shetty, 2020: Food diversity and indigenous food systems to combat diet-linked chronic diseases. *Current Developments in Nutrition*, **4** (Supplement_1), 3–11. https://doi.org/10.1093/cdn/nzz099

361. Bildfell, R.J., J.W. Mertins, J.A. Mortenson, and D.F. Cottam, 2004: Hair-loss syndrome in black-tailed deer of the Pacific Northwest. *Journal of Wildlife Diseases*, **40** (4), 670–681. https://doi.org/10.7589/0090-3558-40.4.670

362. Byers, J.E., 2021: Marine parasites and disease in the era of global climate change. *Annual Review of Marine Science*, **13** (1), 397–420. https://doi.org/10.1146/annurev-marine-031920-100429

363. Donatuto, J., L. Campbell, C. Cooley, M. Cruz, J. Doyle, M. Eggers, T. Farrow Ferman, S. Gaughen, P. Hardison, C. Jones, D. Marks-Marino, A. Pairis, W. Red Elk, D. Sambo Dorough, and C. Sanders, 2021: Ch. 5. Health & wellbeing. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 159–173. http://nau.edu/stacc2021

364. Norton-Smith, K., K. Lynn, K. Chief, K. Cozzetto, J. Donatuto, M.H. Redsteer, L.E. Kruger, J. Maldonado, C. Viles, and K.P. Whyte, 2016: Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences. Gen. Tech. Rep. PNW-GTR-944. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 136 pp. https://www.fs.usda.gov/treesearch/pubs/53156

365. Doubleday, A., N.A. Errett, K.L. Ebi, and J.J. Hess, 2020: Indicators to guide and monitor climate change adaptation in the US Pacific Northwest. *American Journal of Public Health*, **110** (2), 180–188. https://doi.org/10.2105/ajph.2019.305403

366. State of Oregon, 2021: State of Oregon Climate Equity Blueprint. State of Oregon. https://www.oregon.gov/lcd/cpu/documents/2021_jan_climate-equity-blueprint.pdf

367. Powell, J., S. Menendian, and W. Ake, 2019: Targeted Universalism Policy & Practice. University of California, Berkeley, Haas Institute for a Fair and Inclusive Society. https://belonging.berkeley.edu/sites/default/files/targeted_universalism_primer.pdf?file=1&force=1

368. Filigrana, P., J.I. Levy, J. Gauthier, S. Batterman, and S.D. Adar, 2022: Health benefits from cleaner vehicles and increased active transportation in Seattle, Washington. *Journal of Exposure Science & Environmental Epidemiology*, **32** (4), 538–544. https://doi.org/10.1038/s41370-022-00423-y

369. Rempel, A.R., J. Danis, A.W. Rempel, M. Fowler, and S. Mishra, 2022: Improving the passive survivability of residential buildings during extreme heat events in the Pacific Northwest. *Applied Energy*, **321**, 119323. https://doi.org/10.1016/j.apenergy.2022.119323

370. Adger, W.N., J. Barnett, K. Brown, N. Marshall, and K. O'Brien, 2013: Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, **3** (2), 112–117. https://doi.org/10.1038/nclimate1666

371. Guy, K., 2020: A Security Threat Assessment of Global Climate Change: How Likely Warming Scenarios Indicate a Catastrophic Security Future. Product of the National Security, Military, and Intelligence Panel on Climate Change, Femia, F. and C. Werrell, Eds. The Center for Climate and Security, an Institute of the Council on Strategic Risks, Washington, DC. https://climateandsecurity.org/a-security-threat-assessment-of-global-climate-change/

372. McKelvey, K.S., W.M. Block, T.B. Jain, C.H. Luce, D.S. Page-Dumroese, B.A. Richardson, V.A. Saab, A.W. Schoettle, C.H. Sieg, and D.R. Williams, 2021: Adapting research, management, and governance to confront socioecological uncertainties in novel ecosystems. *Frontiers in Forests and Global Change*, **4**, 644696. https://doi.org/10.3389/ffgc.2021.644696

373. Insley, M. and M. Lei, 2007: Hedges and trees: Incorporating fire risk into optimal decisions in forestry using a no-arbitrage approach. *Journal of Agricultural and Resource Economics*, **32** (3), 492–514. https://doi.org/10.22004/ag.econ.7084

374. Palaiologou, P., A.A. Ager, M. Nielsen-Pincus, C.R. Evers, and M.A. Day, 2019: Social vulnereability to large wildfires in the western USA. *Landscape and Urban Planning*, **189**, 99–116. https://doi.org/10.1016/j.landurbplan.2019.04.006

375. Jasechko, S. and D. Perrone, 2021: Global groundwater wells at risk of running dry. *Science*, **372** (6540), 418–421. https://doi.org/10.1126/science.abc2755

376. Holmes, T.P., E.A. Murphy, and K.P. Bell, 2006: Exotic forest insects and residential property values. *Agricultural and Resource Economics Review*, **35** (1), 155–166. https://doi.org/10.1017/s1068280500010121

377. Warziniack, T., R.G. Haight, D. Yemshanov, J.L. Apriesnig, T.P. Holmes, A.M. Countryman, J.D. Rothlisberger, and C. Haberland, 2021: Ch. 14. Economics of invasive species. In: *Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector*. Poland, T.M., T. Patel-Weynand, D.M. Finch, C.F. Miniat, D.C. Hayes, and V.M. Lopez, Eds. Springer, Cham, Switzerland, 305–320. https://doi.org/10.1007/978-3-030-45367-1_14

378. Wolf, D. and H.A. Klaiber, 2017: Bloom and bust: Toxic algae's impact on nearby property values. *Ecological Economics*, **135**, 209–221. https://doi.org/10.1016/j.ecolecon.2016.12.007

379. Baldauf, M., L. Garlappi, and C. Yannelis, 2020: Does climate change affect real estate prices? Only if you believe in it. *The Review of Financial Studies*, **33** (3), 1256–1295. https://doi.org/10.1093/rfs/hhz073

380. Hino, M. and M. Burke, 2021: The effect of information about climate risk on property values. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (17), e2003374118. https://doi.org/10.1073/pnas.2003374118

381. Headwaters Economics, 2016: Do Insurance Policies and Rates Influence Development on Fire-Prone Lands? Headwaters Economics, 14 pp. https://headwaterseconomics.org/wildfire/solutions/insurance-wildfire-home-development/

382. Garber-Yonts, B.E., 2004: The Economics of Amenities and Migration in the Pacific Northwest: Review of Selected Literature with Implications for National Forest Management. Gen. Tech. Rep. PNW-GTR-617. U.S. Department of Agriculture, Forest Service. Pacific Northwest Research Station, Portland, OR, 48 pp. https://doi.org/10.2737/pnw-gtr-617

383. Lambers, J.H.R., A.F. Cannistra, A. John, E. Lia, R.D. Manzanedo, M. Sethi, J. Sevigny, E.J. Theobald, and J.K. Waugh, 2021: Climate change impacts on natural icons: Do phenological shifts threaten the relationship between peak wildflowers and visitor satisfaction? *Climate Change Ecology*, **2**, 100008. https://doi.org/10.1016/j.ecochg.2021.100008

384. Wobus, C., E.E. Small, H. Hosterman, D. Mills, J. Stein, M. Rissing, R. Jones, M. Duckworth, R. Hall, M. Kolian, J. Creason, and J. Martinich, 2017: Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environmental Change*, **45**, 1–14. https://doi.org/10.1016/j.gloenvcha.2017.04.006

385. Sánchez, J.J., R. Marcos-Martinez, L. Srivastava, and N. Soonsawad, 2021: Valuing the impacts of forest disturbances on ecosystem services: An examination of recreation and climate regulation services in U.S. national forests. *Trees, Forests and People*, **5**, 100123. https://doi.org/10.1016/j.tfp.2021.100123

386. Vose, J.M., J.S. Clark, C.H. Luce, and T. Patel-Weynand, 2016: Effects of Drought on Forests and Rangelands in the United States: A Comprehensive Science Synthesis. Gen. Tech. Rep. WO-93b. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 289 pp. https://doi.org/10.2737/wo-gtr-93b

387. Paine, L.A., 1971: Accident Hazard Evaluation and Control Decisions on Forested Recreation Sites. Res. Paper PSW-68. U.S. Department on Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, 10 pp. https://www.fs.usda.gov/research/treesearch/28669

388. Burns, S.F., R. Pirot, K. Williams, and S. Sobieschezk, 2015: Massive debris flow event on Pacific Northwest volcanoes, USA, November 2006: Causes, effects and relationship to climate change. In: *Engineering Geology for Society and Territory - Volume 2*, Lollino, G., D. Giordan, G.B. Crosta, J. Corominas, R. Azzam, J. Wasowski, and N. Sciarra, Eds. Cham, Switzerland. Springer, 545–550. https://doi.org/10.1007/978-3-319-09057-3_90

389. Gellman, J., M. Walls, and M. Wibbenmeyer, 2022: Wildfire, smoke, and outdoor recreation in the western United States. *Forest Policy and Economics*, **134**, 102619. https://doi.org/10.1016/j.forpol.2021.102619

390. Idaho DHW, n.d.: Activity Guidelines for Wildfire Smoke Events. Idaho Department of Health and Welfare. https://idhsaa.org/asset/sports%20medicine/wildfire-table-for-schools%20mkedits.pdf

391. Inkley, D., 2013: New report addresses climate change and freshwater fish. *Fisheries*, **38** (11), 518–518. https://doi.org/10.1080/03632415.2013.848402

392. Weiskopf, S.R., O.E. Ledee, and L.M. Thompson, 2019: Climate change effects on deer and moose in the Midwest. *The Journal of Wildlife Management*, **83** (4), 769–781. https://doi.org/10.1002/jwmg.21649

393. Kourantidou, M., D. Jin, and E.J. Schumacker, 2022: Socioeconomic disruptions of harmful algal blooms in indigenous communities: The case of Quinault Indian Nation. *Harmful Algae*, **118**, 102316. https://doi.org/10.1016/j.hal.2022.102316

394. Moss, L.A.G. and R.S. Glorioso, Eds., 2014: *Global Amenity Migration: Transforming Rural Culture, Economy and Landscape*. New Ecology Press, Kaslo, BC, 435 pp.

395. Winkler, R.L. and M.D. Rouleau, 2021: Amenities or disamenities? Estimating the impacts of extreme heat and wildfire on domestic US migration. *Population and Environment*, **42** (4), 622–648. https://doi.org/10.1007/s11111-020-00364-4

396. Abrams, J.B., H. Gosnell, N.J. Gill, and P.J. Klepeis, 2012: Re-creating the rural, reconstructing nature: An international literature review of the environmental implications of amenity migration. *Conservation and Society*, **10** (3), 270–284. https://doi.org/10.4103/0972-4923.101837

397. Rickman, D.S. and H. Wang, 2020: Whither the American west economy? Natural amenities, mineral resources and nonmetropolitan county growth. *The Annals of Regional Science*, **65** (3), 673–701. https://doi.org/10.1007/s00168-020-00999-z

398. Hjerpe, E., C.A. Armatas, and M. Haefele, 2022: Amenity-based development and protected areas in the American West. *Land Use Policy*, **116**, 106064. https://doi.org/10.1016/j.landusepol.2022.106064

399. Donatuto, J., L. Campbell, and W. Trousdale, 2020: The "value" of values-driven data in identifying Indigenous health and climate change priorities. *Climatic Change*, **158** (2), 161–180. https://doi.org/10.1007/s10584-019-02596-2

400. Wang, C.J., H.A. Schaller, K.C. Coates, M.C. Hayes, and R.K. Rose, 2020: Climate change vulnerability assessment for Pacific lamprey in rivers of the western United States. *Journal of Freshwater Ecology*, **35** (1), 29–55. https://doi.org/10.1080/02705060.2019.1706652

401. Gaughen, S., S. Bliss, J. Mauck, and T. Romero, 2021: Ch. 8. Cultural resources. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 210–221. http://nau.edu/stacc2021

402. Long, J.W. and F.K. Lake, 2018: Escaping social-ecological traps through tribal stewardship on national forest lands in the Pacific Northwest, United States of America. *Ecology and Society*, **23** (2). https://doi.org/10.5751/es-10041-230210

403. Long, J.W., F.K. Lake, R.W. Goode, and B.M. Burnette, 2020: How traditional tribal perspectives influence ecosystem restoration. *Ecopsychology*, **12** (2). https://doi.org/10.1089/eco.2019.0055

404. Lake, F.K., V. Wright, P. Morgan, M. McFadzen, D. McWethy, and C. Stevens-Rumann, 2017: Returning fire to the land: Celebrating traditional knowledge and fire. *Journal of Forestry*, **115** (5), 343–353. https://doi.org/10.5849/jof.2016-043r2

405. Voggesser, G., K. Lynn, J. Daigle, F.K. Lake, and D. Ranco, 2014: Ch. 9. Cultural impacts to tribes from climate change influences on forests. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., B. Colombi, and R. Pandya, Eds. Springer, Cham, Switzerland, 107–118. https://doi.org/10.1007/978-3-319-05266-3_9

406. Warner, E.A.K., 2015: Everything old is new again: Enforcing tribal treaty provisions to protect climate change-threatened resources. *Nebraska Law Review*, **94** (4). https://digitalcommons.unl.edu/nlr/vol94/iss4/4

407. Whyte, K., 2017: Indigenous climate change studies: Indigenizing futures, decolonizing the Anthropocene. *English Language Notes*, **55** (1), 153–162. https://doi.org/10.1215/00138282-55.1-2.153

408. Whyte, K.P., 2013: Ch. 2. Justice forward: Tribes, climate adaptation and responsibility. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., B. Colombi, and R. Pandya, Eds. Springer, Cham, Switzerland, 9–22. https://doi.org/10.1007/978-3-319-05266-3_2

409. Flores, D. and G. Russell, 2020: Ch. 5.5. Integrating tribes and culture Into public land management. In: *Northeastern California Plateaus Bioregion Science Synthesis*. Dumroese, R.K. and W.K. Moser, Eds. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 177–185. https://www.fs.usda.gov/research/treesearch/60223

410. Long, J., F.K. Lake, K. Lynn, and C. Viles, 2018: Ch. 11. Tribal ecocultural resources and engagement. In: *Synthesis of Science to Inform Land Management Within the Northwest Forest Plan Area*. Spies, T.A., P.A. Stine, R. Gravenmier, J.W. Long, and M.J. Reilly, Eds. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 851–917. https://www.fs.usda.gov/research/treesearch/56333

411. Donatuto, J., E.E. Grossman, J. Konovsky, S. Grossman, and L.W. Campbell, 2014: Indigenous community health and climate change: Integrating biophysical and social science indicators. *Coastal Management*, **42** (4), 355–373. https://doi.org/10.1080/08920753.2014.923140

412. Fink, J.H., 2019: Contrasting governance learning processes of climate-leading and -lagging cities: Portland, Oregon, and Phoenix, Arizona, USA. *Journal of Environmental Policy and Planning*, **21** (1), 16–29. https://doi.org/10.1080/1523908x.2018.1487280.

413. Levenda, A.M., J. Richter, T. Miller, and E. Fisher, 2019: Regional sociotechnical imaginaries and the governance of energy innovations. *Futures*, **109**, 181–191. https://doi.org/10.1016/j.futures.2018.03.001.

414. Davies, I.P., R.D. Haugo, J.C. Robertson, and P.S. Levin, 2018: The unequal vulnerability of communities of color to wildfire. *PLoS ONE*, **13** (11), 0205825. https://doi.org/10.1371/journal.pone.0205825

415. Ward, E.J., J.H. Anderson, T.J. Beechie, G.R. Pess, and M.J. Ford, 2015: Increasing hydrologic variability threatens depleted anadromous fish populations. *Global Change Biology*, **21** (7), 2500–2509. https://doi.org/10.1111/gcb.12847

416. Kurtz, K., B. Hins-Turner, A. Abbott, L. Eschenbach, L. Williams, and M. Nepean, 2021: Roadmap to a Green Economy: Aligning Education, Workforce and Economic Development Systems. Pacific Education Institute, 59 pp. https://wsac.wa.gov/sites/default/files/2021-03-17-Green-Economy-Report.pdf

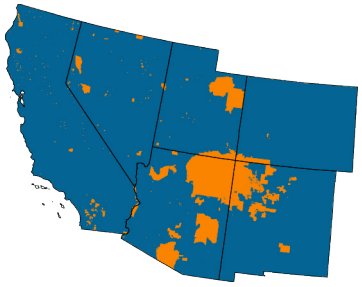
417. Van de Graaf, T. and B.K. Sovacool, 2020: *Global Energy Politics*. Wiley, 240 pp. https://www.wiley.com/en-us/global+energy+politics-p-9781509530489

418. WA DNR, 2020: Electric Utilities Wildland Fire Prevention Task Force–Final Report. Washington Department of Natural Resources, 17 pp. https://www.dnr.wa.gov/publications/rp_fire_electric_utility_taskforce_report.pdf

419. U.S. Federal Government, 2021: U.S. Climate Resilience Toolkit: Energy [Webpage]. https://toolkit.climate.gov/topics/energy-supply-and-use

Fifth National Climate Assessment: Chapter 28

# Southwest



# Chapter 28. Southwest

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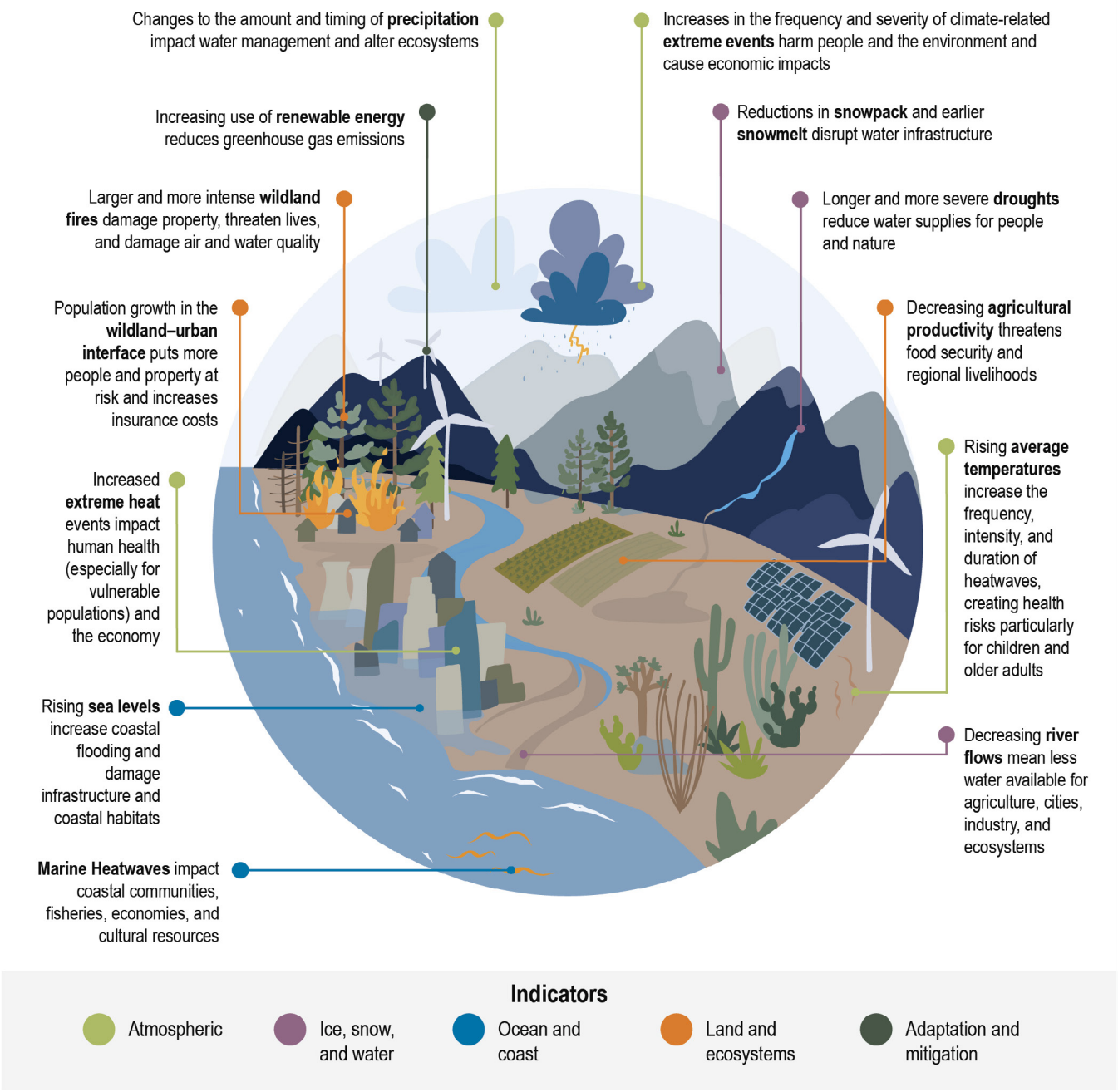
# Introduction

The Southwest encompasses diverse natural ecosystems, vibrant cultures, and productive economies. This vast region spans nearly 700,000 square miles, or 18% of the US land area.[1] The Southwest is home to more than 60 million people and is among the fastest growing and most economically productive areas of the country. Southwest ecosystems provide society with food, energy, and water; regulate climate; protect against disasters and disturbances; and offer the settings and inspiration for meaningful social, cultural, recreational, and spiritual experiences (Figure 8.17).

Climate change is negatively impacting human health and well-being (KM 15.1), cultural heritage, property, built infrastructure, economic prosperity, natural capital, and ecosystem services across the Southwest (Figure 28.1). Impacts include rising air temperatures[2] and sea surface temperatures, both attributable in part to human activities;[3] changes to the timing, form, and amount of precipitation;[4,5,6] sea level rise and associated flooding events;[7] increases in extreme heat events;[8] summertime heat stress[9,10] and heat-related mortality;[11] surface and groundwater reductions;[12,13,14,15,16] increased wildfire risks;[17,18,19,20,21] and changes to ocean chemistry. These impacts pose heightened risks to overburdened and frontline communities and to Indigenous Peoples (KMs 4.2, 15.2, 16.1).

## Climate Change Indicators, Impacts, and Responses in the Southwest




**Indicators highlight important climate impacts and adaptation and mitigation efforts.**

**Figure 28.1.** Indicators track the impacts of climate change on the atmosphere; ice, snow, and water; ocean and coast; and land and ecosystems, as well as adaptation and mitigation efforts. Monitoring these indicators helps us understand how impacts are experienced and how to adapt to risks. See Appendix 4 for more Indicators. Figure credit: Arizona State University. See figure metadata for additional contributors.

Southwest ecosystems transition from deserts and grasslands in hotter and lower elevations to forests and alpine meadows in cooler, higher elevations. The region supports important terrestrial and marine biodiversity and ecosystems, including the Sonoran Desert, the Sierra Nevada, and the Pacific Coast. The southern deserts commonly see temperatures between 105° and 115°F, and Phoenix has the hottest climate of all major US cities. The California coast stretches 3,400 miles (5,500 km), and its coastal wetlands provide critical habitat for fish and wildlife, protect water quality, and buffer against storms and floods.

The region is heavily urbanized, with 9 out of 10 people living in cities such as Albuquerque, Denver, Las Vegas, Los Angeles, Phoenix, Salt Lake City, and San Francisco. The region is also a major hub for software innovation, information technology, and semiconductor manufacturing. California's economy alone contributed more than $3.21 trillion (in 2022 dollars) to the US GDP in 2021, about 12% of the total US economy.[22] The region also encompasses expansive rural areas with livelihoods centered on ranching, mining, agriculture, and tourism.

Indigenous Peoples and Tribal lands are essential to the social, cultural, and geographic identity of the region. The Southwest is home to 182 Federally Recognized Tribes,[23] as well as numerous state-recognized Tribes and Tribes seeking state or federal recognition. California has the largest number of Federally Recognized Tribes (109) and the largest Indigenous population of any state.[23] Arizona, New Mexico, Colorado, and Utah are home to seven of the most populous Tribes, ranging from 10,000 to more than 300,000 members. Nine Tribes in the Southwest are considered "large land-holding Tribes," five of which are among the ten largest reservations in the US, ranging in size from 600,000 to 16 million acres. The largest US federal Indian reservation—the 16-million-acre Navajo Nation Reservation—occupies portions of Arizona, New Mexico, and Utah.

The Federal Government manages nearly half of the total land area of the region through national parks, forests, fish and wildlife reserves, military installations, and public lands.[24] In Nevada, the Federal Government is responsible for managing more than 80% of the total acreage of the state.[24] Thus, the Federal Government is central to adaptation and mitigation in the Southwest.

Over the past five years, climate change impacts in the Southwest have become increasingly apparent and widespread.[25] At the same time, understanding and modeling of how these impacts affect specific sectors and processes have improved. For instance, advances have been made in understanding and modeling of water,[26,27,28] food and agriculture,[29] wildfire,[19] invasive species, biodiversity loss (KM 8.2), ecosystem transformations, human health,[30] and human migration across the Southwest.[31,32] Furthermore, research has advanced understanding and modeling of interdependencies, feedbacks, and cascading risks for interconnected systems (KM 18.1) such as the food–energy–water nexus (KM 18.3).[33,34]

To address these climate change impacts, governments, nongovernmental organizations, and private enterprises are increasingly responding with planning and actions to reduce current and future risks and increase adaptive capacity. Adaptation efforts that are effective, feasible, and just—including nature-based solutions such as green infrastructure for flood mitigation—have been shown to reduce climate risk, increase resilience, and provide co-benefits to related societal goals (KM 8.3).[35] There is an awareness of new approaches to equity and environmental justice for frontline communities, as well as Indigenous Peoples (KM 16.2) across the Southwest. These approaches recognize, protect, and apply diverse knowledge systems, including Indigenous Knowledges (KM 16.3). Social science has also improved our understanding of inclusive, participatory, and collaborative decision-making to solve problems in this region and beyond.[36,37,38]

While this chapter focuses on climate impacts, risks, and adaptation actions in the Southwest, it also recognizes efforts underway to mitigate greenhouse gas emissions (Figure 32.20) throughout the region at multiple scales. California, Colorado, and New Mexico are members of the US Climate Alliance, committed to reducing net greenhouse gas (GHG) emissions in line with the Paris Agreement (KM 32.5). California has committed to carbon neutrality by 2045[39,40] and released a detailed plan with targets to achieve this goal,[41] as well as augmenting funding across sectors.[42] Both Colorado and New Mexico have statewide greenhouse gas reduction goals.[43,44] At the local level, dozens of cities in all Southwest states are committed to emissions reductions in line with the Paris Agreement through the bipartisan Climate Mayors network (KM 32.5). For example, the Phoenix Climate Action Plan states that the city is on track to meet its goal of 50% reduction in GHG emissions (below its 2018 baseline) by 2030 and is committed to carbon neutrality by 2050.

## Key Message 28.1

## Drought and Increasing Aridity Threaten Water Resources

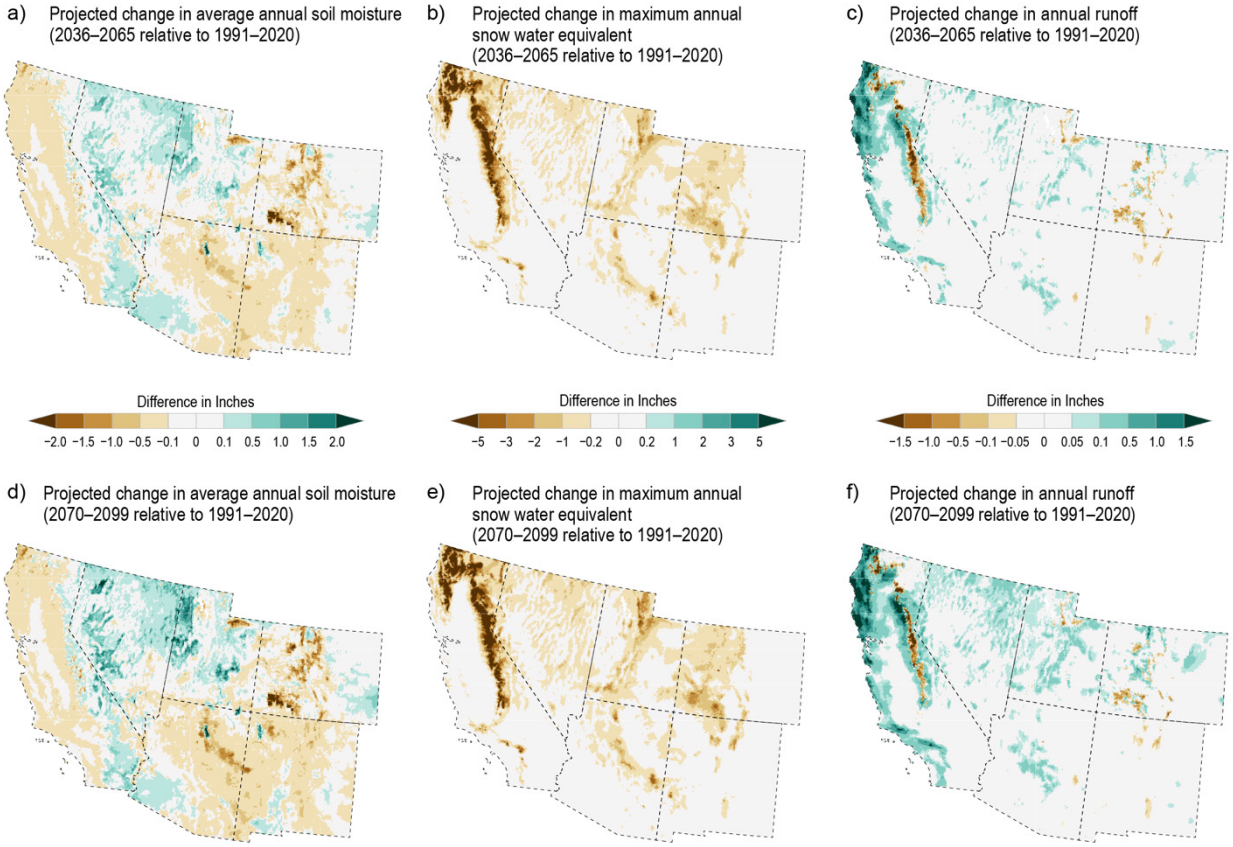
Climate change has reduced surface water and groundwater availability for people and nature in the Southwest (*very high confidence*), and there are inequities in how these impacts are experienced (*high confidence*). Higher temperatures have intensified drought and will lead to a more arid future (*very likely*, *high confidence*); without adaptation, these changes will exacerbate existing water supply–demand imbalances (*likely*, *high confidence*). At the same time, the region is experiencing more intense precipitation events, including atmospheric rivers, which contribute to increased flooding (*high confidence*). Flexible and adaptive approaches to water management have the potential to mitigate the impacts of these changes on people, the environment, and the economy (*medium confidence*).

### *Drought and Aridification*

The Southwest region is historically arid and marked by episodes of intense drought and precipitation (KM 4.1).[45,46] Climate change is exacerbating these conditions, as increasing temperatures are leading to hotter extreme heat events, drier soils, greater atmospheric evaporative demand, and reduced flows in major river basins such as the Colorado and Rio Grande.[14,47,48,49,50] For example, between 1913 and 2017, annual average discharge from the Colorado River decreased by 9.3% for each degree Celsius of warming (Box 28.1).[49] Additionally, since 2000 the Southwest has experienced an exceptional "megadrought"—defined as an episode of intense aridity that persists for multiple decades—that is recognized as the driest 22-year period in 1,200 years.[51]

Mountain snowpack is one of the most important sources of water in the Southwest, serving as a natural reservoir to supply water to drier, lower elevations for irrigated agricultural, municipal and industrial uses, and ecosystems (KM 4.1). Observed declines in western snowpack over the last century have been predominantly driven by warming trends,[4] leading to smaller snowpack volumes, higher-elevation snow lines, and earlier snowmelt (KM 3.4).[6,52] These processes are exacerbated by the deposition of dust and other light-absorbing particles on snowpack, which accelerates snowmelt.[53] The resulting decrease in snow cover also reduces the albedo, or reflectivity, of the land surface, resulting in a positive feedback cycle that further increases solar radiation absorption, warming, and snowmelt.[49,54,55] These changing snowpack dynamics are expected to have different influences on the timing and volume of snowmelt-driven streamflow in different basins,[56] potentially disrupting the ability of existing water infrastructure, including hydropower, to meet the region's needs[5,49] and altering ecosystem dynamics. Persistent low-snow years are projected to occur in the next half century if climate change continues unabated (Figure 28.2).[5]

## Projected Changes in Soil Moisture, Snow Water Equivalent, and Runoff




**Climate change is projected to reduce snow water equivalent and alter trends in soil moisture and annual runoff.**

**Figure 28.2.** These maps show projected average mid-21st-century (2036–2065; top row) and late-21st-century (2070–2099; bottom row) differences in annual soil moisture, snow water equivalent (the amount of water contained within the snowpack), and runoff over the Southwest region relative to the baseline period, 1991–2020. The data in these maps come from a land-surface hydrological model that simulates different parts of the water and energy balance. The model takes temperature and precipitation data from an ensemble of downscaled Coupled Model Intercomparison Project, Phase 5 (CMIP5) global climate models using an intermediate scenario (RCP4.5)[57] to create future projections of soil moisture, snow water equivalent, and runoff.[58] Warming temperatures and precipitation variability are expected to reduce snow water equivalent and alter trends in soil moisture and annual runoff (KM 4.1). The historical record shows that the climatology of 1991–2020 was substantially warmer than the climatology of preceding 30-year periods. Thus, the areas of projected lower soil moisture, snow water equivalent, and runoff in this figure, especially at higher elevations, present marked deficits in comparison to 30-year periods in the 20th century. There are also areas of projected increases in soil moisture and runoff. Some CMIP5 global climate models project increased precipitation over parts of the Southwest, and when these are included in calculating average soil moisture or runoff, the result indicates wetter conditions in some locations, predominantly in Nevada, Utah, southwest Arizona, and southeast California. For more detail on variability, Figures 4.5, 4.6, and 4.7 show data from the same source that illustrate the wet to dry range of projections for the mid-21st century. Figure credit: New Mexico State University; Arizona State University; University of Nevada, Reno; NOAA NCEI; and CISESS NC.

In addition to extended periods of record-low precipitation, higher temperatures driven by climate change have increased evapotranspiration and reduced soil moisture, which can reduce the volume of runoff produced from a given amount of precipitation.[16,47,50,59] These trends have negatively impacted natural resource management and agricultural production (KM 11.1) by increasing stress on vegetation.[60] Coupled with increases in demand and subsequent water withdrawals, reduced streamflow has caused many

of the region's lakes and reservoirs, such as the Great Salt Lake, to reach historically low water levels.[61] Furthermore, greater variability in streamflow threatens the region's ability to consistently produce and use hydropower, impacting a typically reliable and low-carbon source of energy.[62]

Climate warming will also reduce groundwater recharge from rainfall, snowmelt, and runoff in some areas, thereby reducing groundwater storage.[63,64] These effects are exacerbated by groundwater pumping to satisfy the needs of agricultural irrigation,[65,66] which is the biggest consumer of fresh water in the region. The Central Valley aquifer of California is one of the most stressed aquifers in the world; during the 2012–2016 drought, about two-thirds of the valley's surface water deficit was due to groundwater pumping, which caused land subsidence (the gradual sinking of land) in some areas[67] and declines in groundwater quality.

## Flooding

Despite the region's increasing aridity, flooding from extreme precipitation events (KM 3.5) and snowmelt conditions (KM 4.1) also poses a threat to life and property, as well as to freshwater ecosystems.[68,69] Due to climate change, snowmelt-driven flooding is expected to occur earlier in the year due to earlier runoff.[70] Moreover, atmospheric rivers, which have driven much of historical flooding in the region, are expected to intensify under a warming climate.[71,72] Flooding from sea level rise may also threaten water infrastructure and supplies in areas such as the Sacramento–San Joaquin Bay Delta region.[73,74]

## Disproportionate Impacts

Critically, the impacts of these climate-driven changes are experienced disproportionately by certain communities in the region, including Indigenous communities (KM 16.1). A lack of clean water and sanitation services in Indigenous communities came to national light in 2020 due to COVID-19, which spread 3.5 times faster among Indigenous than non-Indigenous communities in the initial stage of the pandemic,[75] due in part to the lack of access to potable water in some Indigenous communities. A major impediment to water access is the cost of water infrastructure, which averages $600 per acre-foot of water for non-Indigenous families with piped delivery, compared to $43,000 per acre-foot of water for Navajo families relying on hauled water (no dollar year available).[76,77] Furthermore, many Tribes in the region continue to lack access to water because their water rights have not been adjudicated through settlements or other processes, which could further exacerbate water shortages for other users.[78]

Other examples of overburdened communities experiencing disproportionate water-related impacts of climate change include certain Black communities, which face disproportionately higher flood risk in Los Angeles,[79] and Hispanic and low-wealth communities, which receive lower-quality drinking water[80] and may be systematically excluded from water management processes (KM 4.3).[81]

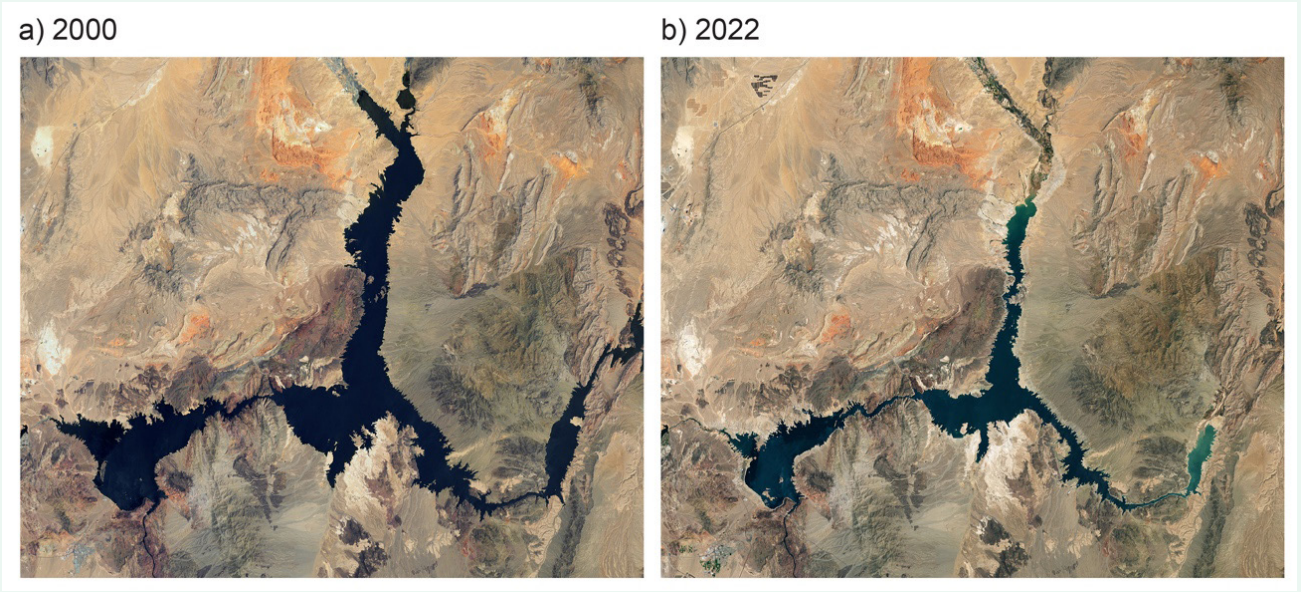
## Adaptation Pathways

In response to these interrelated climate challenges, people across the Southwest have implemented adaptive water governance and management approaches. Examples include California's Sustainable Groundwater Management Act[82] and various conservation and drought response measures in the Colorado River basin,[37,38,83] which incentivize collaboration among diverse participants to develop innovative solutions (KM 12.4). Transitions toward more sustainable water management under climate change also include innovative infrastructure (e.g., enhanced aquifer storage, recharge, and recovery) and institutional practices (e.g., integrative land and water management practices, changes in rate structures, water sharing agreements, and reservoir operations).[84,85,86,87] Social science studies in Southwest cities such as Denver, Phoenix, and Las Vegas indicate widespread support for innovative management strategies for urban water sustainability[88] and opportunities for targeted educational interventions for demand management strategies based on residents' attitudes toward climate change.[89] The extent to which these adaptation actions mitigate changes in water availability depends on interacting climate and social dynamics (KM 3.4).

## Box 28.1. First Water Shortage Declaration on the Colorado River

In response to more than 22 years of historic drought exacerbated by climate change and a growing imbalance between water supply and demand in the Southwest, the US Bureau of Reclamation declared the first-ever water shortage on the Colorado River in August 2021 (Figure 4.18).[90] The decision came after the agency projected that the water level in Lake Mead, the Nation's largest reservoir, would fall to 1,066 feet above sea level, or just 36% of capacity, by the end of 2021, the lowest level since the reservoir was initially filled in the 1930s (Figure 28.3). In addition to impacting water supply reliability for all users, low reservoir levels could disrupt hydropower generation, which provides electricity to several communities in the region. The initial round of water supply cuts implemented under the declaration, following previously negotiated policies, affected Arizona, Nevada, and Mexico, with Arizona farmers taking the biggest cuts. Since then, deeper and more widespread cuts, as well as calls for additional conservation measures, have been made and are expected to expand as climate change impacts continue. In response, the federal governments of the United States and Mexico, the seven US Colorado River basin states, and Indigenous Peoples are developing a range of adaptation pathways and solutions to enhance long-standing collaboration on the Colorado River (KM 16.3), including modeling the impact of more extreme climate change scenarios on water resources in the basin. Multisector conservation and demand management is seen by many as a major solution. Farms can reduce agricultural consumption by increasing water-use efficiency using technologies such as drip irrigation and alternative crop choice. Urban and industrial water conservation, recycling, and reuse improvements could support "water-smart" and economically productive industries in the Southwest. Through a partnership with Mexico on coastal water desalination, the region could free up Colorado River water for the United States while providing Mexico with a secure new supply.[91] Desalination proposals, however, have raised concerns about carbon-intensive energy demands, cost, brine management, and inequitable impacts on Mexico, including environmental impacts from brine disposal. Innovative, decentralized water treatment facilities could directly benefit communities in both countries, including those on Tribal lands.

### Satellite Images of Lake Mead




**Lake Mead water levels have declined, with potential water supply implications for millions of people.**

**Figure 28.3.** Lake Mead, the largest reservoir in the US, supplies water to tens of millions of people across the Southwest; irrigates millions of acres of agricultural land; supports biodiversity, cultural heritage, ecosystems, and ecosystem services; and provides recreational opportunities. From 2000 (**a**) to 2022 (**b**), the water levels in Lake Mead declined from 98% to just 27% of its capacity, as shown in these satellite images. Satellite images: NASA Earth Observatory.

## Key Message 28.2

## Adaptation Efforts Increase to Address Accelerating Impacts to the Region's Coast and Ocean

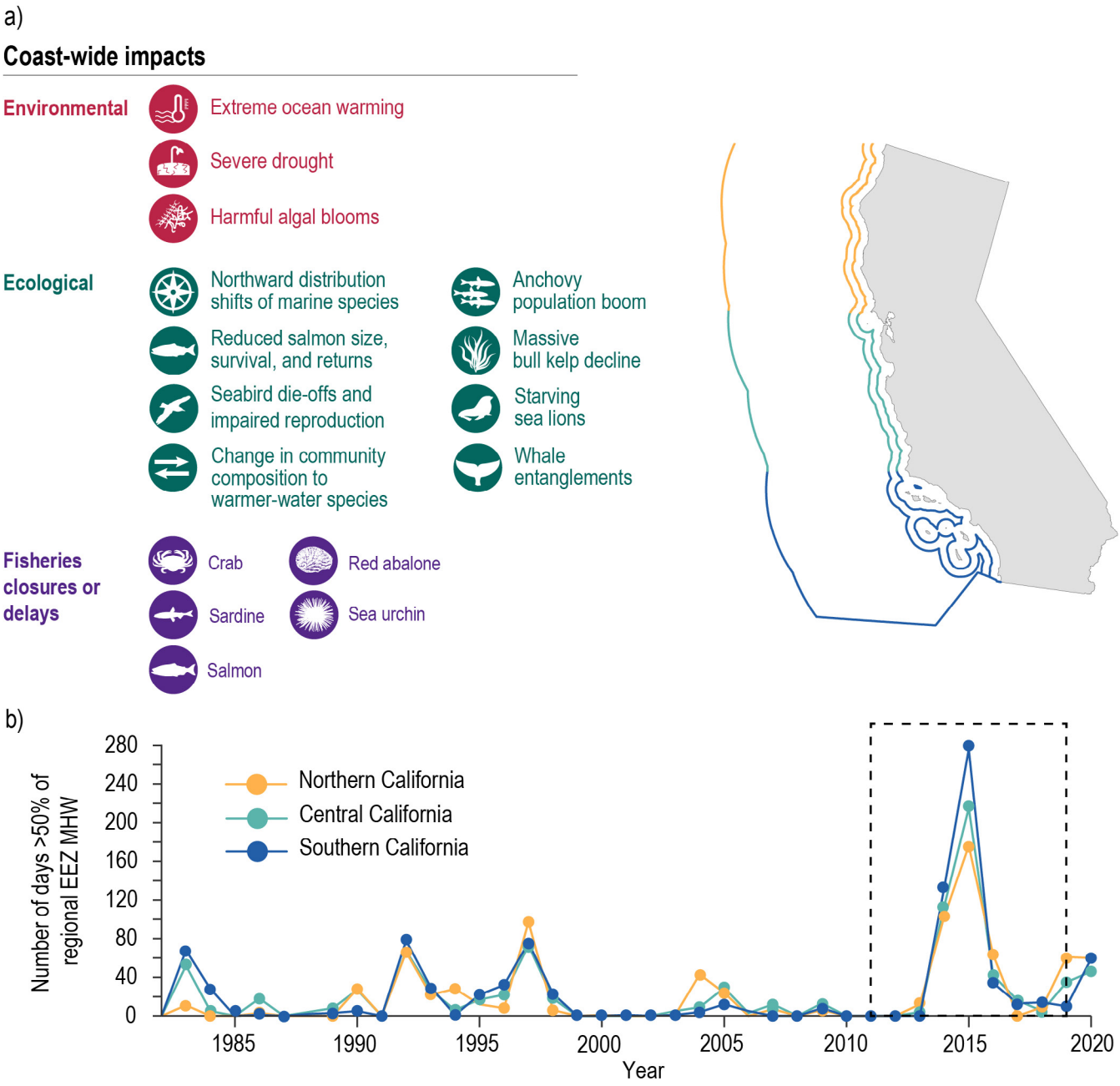
Large-scale marine heatwaves and harmful algal blooms have caused profound and cascading impacts on marine coastal ecosystems and economies (*high confidence*). Without implementation of adaptation or emissions-reductions measures, human-caused warming will drive more frequent and longer marine heatwaves (*very likely*, *very high* confidence), amplifying negative coastal effects (*medium confidence*). Sea level rise, along with associated impacts such as flooding and saltwater intrusion, will have severe and disproportionate effects on infrastructure, communities, and natural resources (*likely*, *very high confidence*). The California State Government has applied climate science to planning and decision-making for sea level rise, and multiple regions are moving toward climate-informed and adaptive strategies for fisheries (*high confidence*). However, climate planning and adaptation solutions for aquaculture are less clear (*high confidence*).

The coastal region of the Southwest encompasses approximately 3,400 miles of coastline and nearly 70% of the state's 39.4 million people. California's 19 coastal counties employ more than 12 million people[92] and in 2012 accounted for 80% of the state's GDP ($57.25 billion in 2022 dollars).[93] Furthermore, California is showing leadership through adaptation actions nationally.

### Ocean Extremes and Adaptation

California coastal sea surface temperature has increased an average of 0.4°–0.6°F per decade since the 1970s[94] and is projected to increase into the future under climate change (Ch. 2).[95,96] Human-caused warming also contributes to marine heatwaves (MHWs; Figure 28.4), or incidences of exceptionally warm ocean temperatures, which have already had significant impacts on human and natural systems (Box 10.1).[97,98,99,100] The change in average cumulative intensification of MHWs for the entire US coast is presented in Figure A4.11. As the ocean warms, including in California coastal waters, MHWs increasingly exceed thermal limits of ecosystems, amplifying impacts[99] including shifts in marine species composition,[101] lower abundance and nutritional quality of important small prey fishes,[102,103] and a potential influence on mass seabird mortalities and reproduction.[104,105] Similarly, Tribal/Indigenous Traditional Knowledge demonstrates significant declines in five coastal species of cultural significance for the Tolowa Dee-ni' Nation, the Cher-Ae Heights Indian Community of the Trinidad Rancheria, the Wiyot Tribe, and the InterTribal Sinkyone Wilderness Council, a Tribal consortium of ten Tribal Nations.[106] Such ecological changes disproportionately impact coastal communities and economies (KM 9.3),[107,108,109] including cultural resources for Indigenous Peoples (KM 15.2).[106,110] The 2014–2016 Northeast Pacific marine heatwave was followed by others in 2018[111]and 2019–2020.[112] These MHWs can coincide with and contribute to other climate-related extremes such as drought[100] and harmful algal blooms (HABs).[113]

## California Marine Heatwaves




**Pacific marine heatwaves have had coast-wide impacts on ecosystems and fisheries.**

**Figure 28.4.** The 2014–2016 Pacific marine heatwave (MHW) was unusually long and resulted in a variety of impacts for the southwest California coast (**a**). This MHW was followed by less extensive events in 2018 and 2019–2020 (**b**). While impacts like this can be expected to continue, they demonstrate the need and potential for adaptive management and mitigation through an integrated ecosystem approach to managing marine habitats and fisheries. EEZ refers to exclusive economic zone. Figure credit: University of California, Santa Barbara; California Department of Transportation; NOAA NCEI; and CISESS NC.

Commercial and recreational wild fisheries, as well as aquaculture (aquatic farming), will continue to be negatively affected by MHWs and HABs,[107] resulting in severe economic ramifications.[113,114,115,116] Extreme ocean warming events also have compound effects: an MHW contributed to the loss of more than 90% of Northern

California's bull kelp, a foundational species for the ocean ecosystem, resulting in large economic losses in fisheries (Focus on Blue Carbon),[117,118] including the red abalone, a species now listed as critically endangered by the International Union for Conservation of Nature. Further, extreme event–related delays and closures disproportionately impacted smaller-scale fishing operations.[119]

The widespread impacts of MHWs and HABs underscore the need for effective adaptive approaches to fisheries management. While fishers in California are coping with MHWs by fishing in different areas or for different species,[108] it will be challenging to manage fisheries in the long term under extreme warming events.[115] Marine protected areas (MPAs), which are considered a management strategy for climate-driven ocean changes, may not buffer widespread effects of MHWs on species in southern California kelp forests.[120] Adopting an ecosystem approach that considers multiple management options instead of one species in isolation[121,122] appears to improve management under climate change.[123] Applying a more coordinated disaster risk management approach to MHWs and extreme HAB events appears to correspond to better adaptive fisheries management, emphasizing the need for improving coordination and consistency across governing bodies, communities, and fishers on the frontlines (KM 10.3).[124,125]

Human-caused ocean warming coincides with increasing ocean acidification (OA) and declining oxygen levels (hypoxia) of the deeper, more nutrient-rich upwelled coastal waters. Under a very high scenario (RCP8.5), sardines, a commercially and ecologically important species, are predicted to move poleward, resulting in substantial shifts in catch.[109,126] Under the same scenario, increased acidity due to the ocean's chemical response to absorption of carbon dioxide is projected to increase the mortality of calcifying invertebrates (such as oysters and other bivalves), which are important to aquaculture and the food web, and result in a loss of food sources for some fishes and invertebrates.[127]

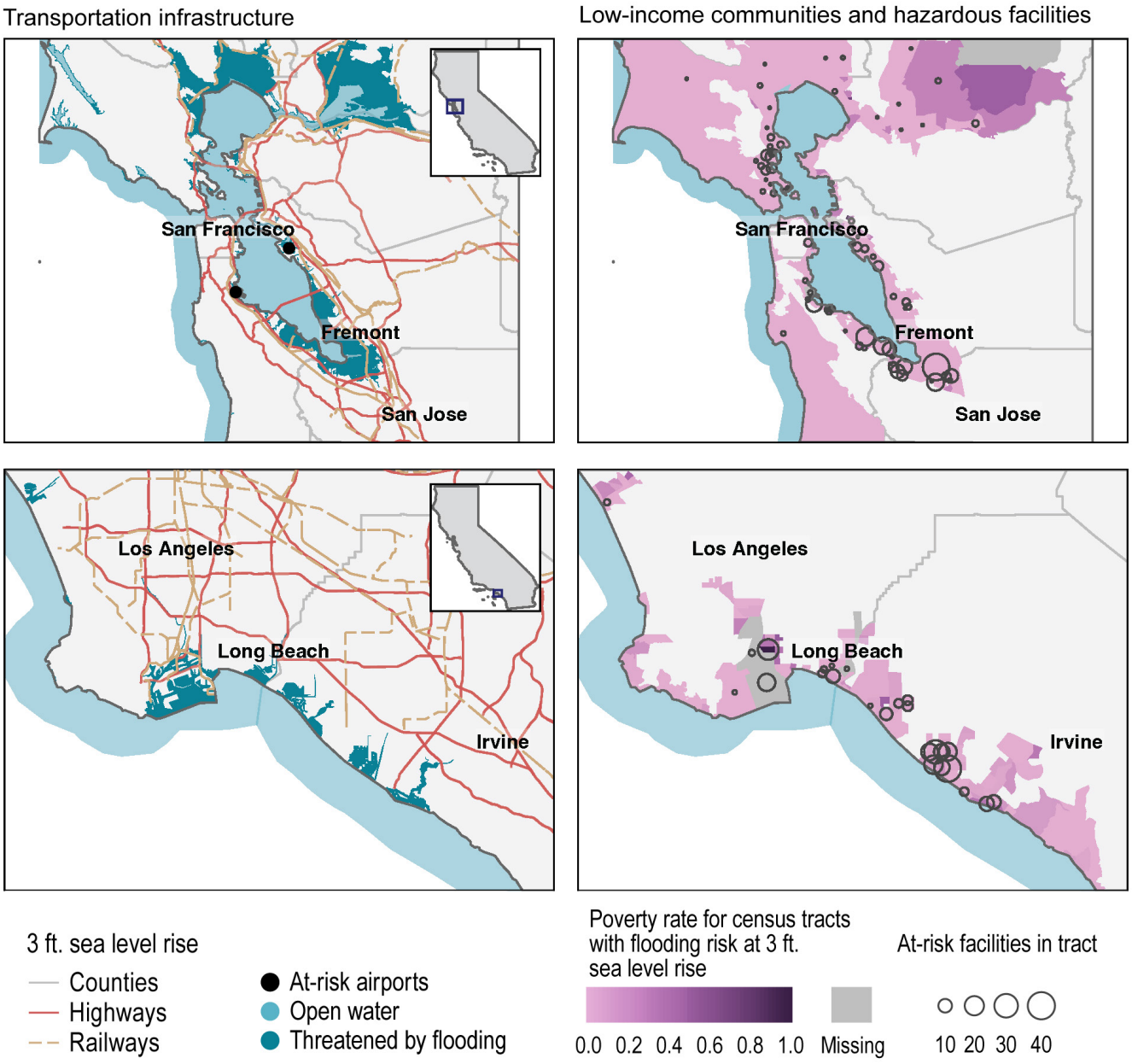
Potential adaptation solutions include an ecosystem management approach to marine habitats and fisheries, as well as enforcing water and land-use regulations, which are expected to buffer some climate impacts.[128] Protection and restoration of foundational eelgrass and kelp forests in California waters provides essential habitat, and these ecosystems can also improve local pH and oxygen conditions.[129,130] The Fishery Ecosystem Plan adopted by Pacific Fishery Management Council in 2013 includes guidance on OA and hypoxia,[128] but additional strategies—such as flexible permitting, better coordination with fishing communities, and adaptable control rules—may be needed to improve outcomes.[131] Nature-based aquaculture solutions, such as conservation and restorative aquaculture, also have potential to mitigate local OA impacts[132,133,134,135] but are just emerging in California.[136]

## *Sea Level Rise Impacts and Adaptation Planning*

Sea level rise (SLR) poses risks to the California coast through an increase in flooding, impacts from storm surges, and loss of coastal habitats and beaches (Figure 28.5; KM 9.1). Seas are projected to rise, on average, 0.79–1.25 feet for the California coastline by 2050, 3.10–6.63 feet by 2100, and 6.11–11.90 feet by 2150 (Intermediate to High scenario).[7] California has more people living below 3.3 feet (1 m) of elevation than any other state except Louisiana;[137] the population living in the mapped 100- and 500-year coastal floodplains increased approximately 10% from 2010 to 2020.[137] SLR is also expected to exacerbate inequities in communities and result in compounding impacts, such as saltwater intrusion polluting groundwater.[7,138,139,140,141,142,143] Furthermore, coastal Tribes in California are observing rising sea levels, which, when combined with the loss of kelp forests, are increasing the risk of coastal erosion, destruction of cultural artifacts, and limited access to traditional shoreline sites.[110]

By 2050, for all emissions pathways, SLR effects on tide and storm surge are expected to cause more frequent moderate to major high tide flood events, and coastal communities are already experiencing minor to moderate high tide flooding (KM 9.1).[7]

## Sea Level Rise Risks to Infrastructure and Communities




**Flooding from sea level rise is expected to affect transportation infrastructure and communities along the California coast, with disproportionate impacts on lower-income communities.**

**Figure 28.5.** These maps show the projected flood risk from 3 feet of sea level rise (SLR), as well as risks to critical infrastructure and surrounding communities, for the San Francisco Bay Area (**top row**) and the coastline from Los Angeles to San Diego (**bottom row**). Panels in the left column show transportation infrastructure threatened by flooding with 3 feet of SLR, while those in the right column show the number of hazardous facilities (indicated by circles) and census tracts at risk of flooding, with purple shading indicating the fraction of population in each census tract with income below the poverty level. Flooding from SLR will impact major transportation infrastructure along the coast; given the locations of hazardous facilities and their overlap with lower-income communities, this flooding will have disproportionate impacts on these communities. Flood risk from SLR is consistent with an Intermediate scenario in the year 2100.[7] Transportation infrastructure includes major airports, highways, and railways. Hazardous facility categories defined by EPA include manufacturing plants, power transmission plants and substations, natural gas pipelines, refineries and oil and gas wells, waste management facilities, landfills and incinerators, and animal operations. Figure credit: Eagle Rock Analytics.

Coastal energy and transportation infrastructure is expected to be negatively impacted by flooding from SLR. The projected inundation of energy substations in low-lying areas during storm events and from extreme SLR under a very high scenario (RCP8.5) is expected to cause electricity service interruptions to thousands of customers and increase maintenance and repair costs.[139] Analysis of California's transportation fuel network found that docks, terminals, and refineries are most exposed to coastal flooding.[143] The California Department of Transportation has begun adaptation planning efforts that consider a variety of strategies beyond hardening infrastructure, including nature-based strategies to limit the impacts of flooding (KM 8.3), as well as planning to avoid loss of coastal resources and access.[144]

Sea level rise and increased coastal flooding will disproportionately impact frontline communities (KM 9.2).[145] The Toxic Tides project found that under a very high scenario (RCP8.5), SLR in California[146,147] would result in increased flooding to over 400 industrial facilities and contaminated sites, including power plants, refineries, and hazardous waste sites, with 440 projected to be at risk of at least one flood event per year by 2100.[148] Any flooding of hazardous sites would increase risks of contamination in surrounding frontline communities.[149]

Residents of affordable housing, typically low-income communities, are especially vulnerable to SLR, with a greater percentage of affordable housing exposed to SLR than the general housing stock in some coastal states.[140] California is in the top four states nationwide with the most units of affordable housing exposed at least four times per year to coastal flooding based on projected sea levels for the year 2050 under a very high scenario (RCP8.5).[140] By 2050, California is also projected to see a 40% increase in the number of units at risk of flooding, compared to 2000.[140] For affordable housing residents, flood risk is compounded by the threat of displacement due to rising property values and rents. Strategic city-level adaptation and resilience efforts, combined with community and infrastructure improvements, could protect these residents from potential displacement.[140,150]

Higher seas are raising the coastal groundwater table, exposing communities to flooding from water that emerges from underground (KMs 9.1, 9.2).[138,141] Communities in low-lying areas such as San Francisco Bay are most at risk, and areas with shallow coastal water tables are projected to see widespread flooding from groundwater emergence.[138,141] Subsidence exacerbates this threat; coastal residents residing in subsiding locations experience an average relative sea level rise of up to four times faster than the global rate.[142,151] These risks have not been well addressed in adaptation planning. Furthermore, the impacts and adaptation needs are expected to be higher than reported if only overland flooding due to SLR—which does not include flooding from subsidence or groundwater intrusion—is considered in community and infrastructure planning.[142]

Adaptation planning for SLR as a field has advanced,[152] as coastal managers have reported an increased concern regarding the threat of SLR and local, regional, and state governments in California apply climate science to decision-making (KM 9.3).[153] California has instituted policies requiring consideration of climate change in state and local government decision-making and infrastructure planning.[154,155,156,157] Specifically for the coast, there is guidance on how to apply SLR risk assessment and projections into planning, including specific guidance for critical infrastructure.[158,159] This landscape of statewide policy and guidance is directly informing local coastal adaptation planning. Of 19 coastal counties, 18 have completed a vulnerability assessment, developed an adaptation policy, and/or updated the state-mandated safety elements of their general plans to include climate adaptation.[160]

While adaptation planning along the California coast has advanced significantly, many of these efforts have not yet been implemented.[160] This is partly because of financing and implementation challenges, especially for local governments that lack resources and must overcome institutional and governance issues (KM 31.5).[152,161] Despite these challenges, California is ahead of many other parts of the US coast in employing adaptation strategies and appears to be well positioned for increased adaptation.[152]

## Key Message 28.3

## Increasing Challenges Confront Food and Fiber Production in the Southwest

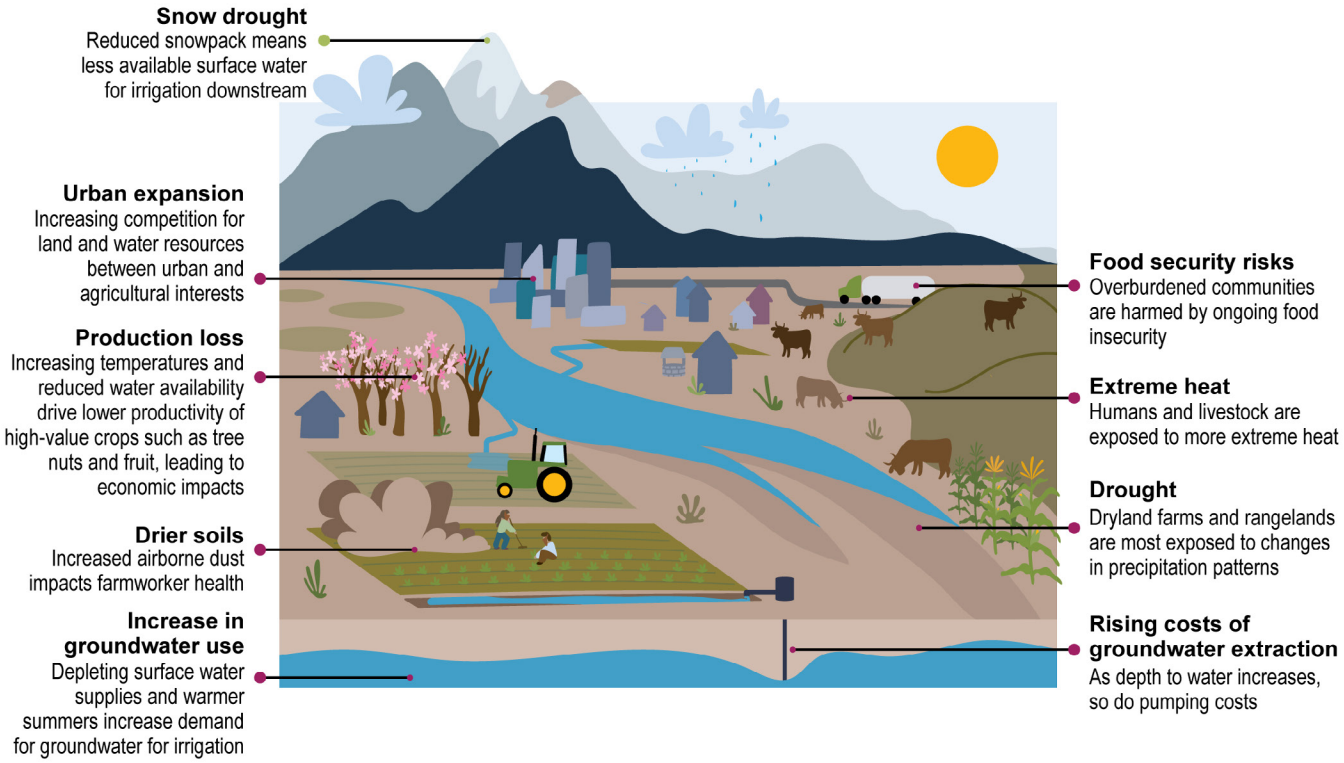
Continuing drought and water scarcity will make it more difficult to raise food and fiber in the Southwest without major shifts to new strategies and technologies (*high confidence*). Extreme heat events will increase animal stress and reduce crop quality and yield, thereby resulting in widespread economic impacts (*likely, high confidence*). Because people in the Southwest have adapted to drought impacts for millennia, incorporating Indigenous Knowledge with technological innovation can offer solutions to protect food security and sovereignty (*medium confidence*).

Across the Southwest, annual average minimum air temperatures, growing degree days, and average number of days above 86°F (the threshold used to define heat zones) are projected to increase due to climate change.[162] By midcentury under intermediate (RCP4.5) and very high (RCP8.5) scenarios, projections show longer growing seasons, a northward shift in plant hardiness zones, and expanded areas of heat stress exposure to crops and livestock (KM 11.1).[162] In California, increasing temperatures are expected to affect the timing of cool-season annual crops and the location of warm-season annual crops.[163] Warmer winters would be detrimental to the chilling requirements for orchard crops.[164] In California, fewer cold snaps are expected to reduce crop exposure to frost;[165] however, "false springs" in the intermountain West are expected to increase vulnerability to late-season freeze events.[166] During summer, a higher probability of heatwaves is expected (KM 2.2).[167] The productivity of some economically important crops, such as upland cotton in Arizona, has already declined because of heat stress.[168] While increased drought is the most prominent climate-driven risk to agriculture in the region, important farming areas such as California's Central Valley also face damage from occasional large floods caused by atmospheric river events.[169]

### *Impacts to Farming*

Farmers and ranchers are particularly at risk from prolonged, severe drought (Figures 28.6, 8.6). Future temperature increases are expected to drive higher rates of evapotranspiration, increasing demand for fresh water for irrigation.[168] The producers most vulnerable to local precipitation deficits are dryland farmers growing rain-fed crops and producers raising livestock on rangelands. Community-based snow-fed irrigation systems in high-elevation watersheds of New Mexico and Colorado, known as *acequias*, are particularly exposed to the shortfalls in annual snowpack.[170] Under increasing aridity, agricultural practices such as fallowing and grazing on rangelands will need careful management to avoid increased wind erosion and dust production from exposed soils.[171] Rising summer temperatures also degrade protective desert soil crusts formed by communities of algae, bacteria, lichens, fungi, or mosses, adding to airborne dust loads.[172] The impacts of increasing aridity on agriculture are therefore twofold because dust deposits on mountain snowpack drive faster melting, depleting the snowpack[173] and resulting in reduced surface water for irrigation. While just 22 of the 216 counties in the region are classified as "farming-dependent" by the USDA,[174] agriculture is an important contributor to state and local economies and US food supply. California leads the Nation in agricultural cash receipts,[175] primarily from fruits, nuts, and vegetables; direct farm sales to consumers; and farm expenditures.[176] Climate change poses risks to both productivity and quality of fruit and vegetable products, requiring adaptations on farms and throughout the supply chain, including changes in crop calendars, nutrient and pest management strategies, post-harvest handling, and preservation methods.[177,178]

## Agriculture and Climate Change in the Southwest US




**Monitoring indicators of climate impacts on agriculture can improve understanding and help with adaptation efforts.**

**Figure 28.6.** Climate change impacts to the Southwest's agriculture include longer growing seasons, a northward shift in plant hardiness zones, expanded areas of heat stress, and higher rates of evapotranspiration, increasing demand for fresh water for irrigation. Monitoring the indicators helps us understand how impacts are experienced and how to adapt to risks. Figure credit: New Mexico State University and Utah State University. See figure metadata for additional contributors.

Reduced crop production due to climate change will carry major economic costs. Drought events have brought significant economic impacts on regional agriculture (KM 19.1); for example, the 2021 drought cost California farming sectors an estimated $1.28 billion (in 2022 dollars) and led to the loss of 8,745 full- or part-time jobs (KM 11.3).[179] Modeling studies indicate that warming temperatures are expected to have a detrimental impact on the yields of almonds,[164] wine grapes,[180] and other high-value crops.[169] Localized adaptation strategies include crop- and locality-specific combinations of irrigation, site management (e.g., use of cover crops and increased fallowing), and cultivar selection.[181] Fallowing as a response to water shortages can bring its own challenges, such as increased dust and weed production, but it can also enhance ecosystem services such as groundwater recharge and improved ecosystem health.[182]

Climate warming is likely to lead to larger, more frequent, and more severe outbreaks of bark beetles, negatively affecting the quality and quantity of timber available to the region's forestry and forest products industries.[183] While wood products are minor economic contributors to the region's inland states, costs could be considerable in California, where the industry has been estimated to contribute $44.8 billion (in 2022 dollars) and 177,000 jobs (KM 7.2).[184]

Over time, agricultural income in the region has become more dependent on crops than livestock.[185] Because most Southwest croplands are irrigated, agriculture in the region had been thought to be less vulnerable to climate change than that in other parts of the country. However, future irrigation supply is

uncertain as it depends on dwindling ground and surface water supplies (KMs 28.1, 4.1). For example, Arizona allows up to 73% of its water to be used for crop production,[186] but the promise of continued irrigation water is less clear given the state's rapidly growing population and decreased flows in the Colorado River.[187] Crop irrigation, mainly of alfalfa, accounts for three-quarters of consumptive water use in the Great Salt Lake basin, where cuts to irrigation use are advocated as the state seeks to prevent total depletion of the lake and associated environmental and public health impacts.[188] Strategies to reduce irrigation water use include switching from gravity flow and sprinklers to more efficient systems,[186] but the costs of conversion can be difficult for farmers when climate change is already reducing yields.[185] Federal insurance programs can assist farmers after climate-related crop or forage loss, providing short-term economic relief from effects of extreme events.[189] However, some research suggests that federal insurance programs provide a disincentive for farmers to adapt to climate change impacts.[189] Non-climate-related stressors can influence the capacity of agricultural communities to adapt to climate impacts.[29] On the plains of Colorado and New Mexico, most rural counties are depopulating due to persistent out-migration of young adults, straining social services and reducing tax revenues.[190] Yet the Southwest also has some of the fastest-growing areas in the US, including high-amenity rural areas and cities expanding into agricultural zones.[191] Urban expansion can increase cropland loss while simultaneously increasing the number of small farms focusing on specialty crops rather than basic commodities,[192,193] placing greater pressure on the region's food supply as drought (KM 28.1)[51] threatens agricultural production.[194]

Livestock production is the dominant use of agricultural land in large areas of the Southwest where crop production is unprofitable or infeasible. Animal agriculture accounts for about one-third of agricultural revenue, with about 70% from cattle.[195] Climate change is expected to reduce the sustainability of cattle production that depends on rangeland ecosystems.[195,196] Negative impacts are expected on the entire livestock food supply chain, affecting production and nutritional quality of forage, livestock health on rangelands and in transport due to heat stress and pest exposure, and shelf life of products during transport and storage.[197,198] Forage from Bureau of Land Management rangelands is expected to decrease in Arizona and New Mexico, but it is less certain whether rangeland forage will hold steady in the central and northern portions of California, Colorado, Nevada, and Utah due to differences in moisture availability during the growing season.[197,199]

## *Cascading Impacts of Climate Change to Agriculture*

The cascading impacts of climate change in combination with urban population increases and other social and cultural factors pose an increasing threat to agriculture in the region.[29] Urban growth in the Southwest has led to competition for water between farms and cities, mirroring global trends.[200] Water transfers from rural to urban areas have been a feature of the Southwest for decades, often with negative consequences for rural and low-income communities.[201,202] To meet water demands for a growing metropolitan region while preserving irrigated croplands, Colorado is experimenting with water policy innovations designed to encourage rural-to-urban transfers while minimizing impacts in rural areas, but adoption has been slow due to distrust on the part of agricultural communities and uncertainty about trade-offs.[202] Market forces in California have encouraged growers to shift to crops with a high economic value but also a large water footprint, such as tree nuts[203,204] and legal cannabis.[205]

## *Frontline Communities and Food Insecurity*

Frontline communities including Hispanic populations, women farmers, migrant farmworkers, and Indigenous Peoples face challenges to water access in their homes as well as food security and health (KM 4.2).[201,206,207] For example, the 2012–2016 drought in California's San Joaquin Valley disrupted farmworkers' employment and reduced food security, water security, and health.[208] Mental health risks are also increasing as farmers and ranchers report moderate to severe levels of anxiety about climate change and the need

to adapt.[209] First-generation and women ranchers are disproportionately vulnerable to climate impacts because of limited experience with drought and weaker connections to rancher networks.[210]

Low-income urban communities are expected to be among the first to suffer food insecurity as climate change reduces the region's food production. Strategies have been proposed to produce more food in urban settings, but these foods often do not reach low-income consumers, who have less access to food distribution systems and often cannot afford to pay the higher prices such foods often command.[211] Indigenous Knowledge has been proposed as a significant resource for climate change adaptation (KM 16.3).[212,213] Because people in the Southwest have adapted to drought impacts for millennia, employing Indigenous Knowledge can allow the region to serve as a "laboratory" for future climate-adapted food systems[214] while enhancing food sovereignty.[215]

## *Adaptation for Agriculture*

Adaptation solutions exist for ranching operations,[196,216] but social and economic barriers, such as distrust of experts, the financial costs and time commitments of innovation, and adherence to tradition, have slowed information uptake.[199] Climate change information is not routinely incorporated into ranchers' risk management decisions[217] and only recently has become a priority in federal agency rangeland management plans.[197]

People across the Southwest are exploring technological adaptations to climate impacts (KM 31.3). Adaptive conservation management approaches that focus on minimizing soil disturbance while maximizing soil cover, biodiversity, and the presence of living roots have been gaining traction with farmers through practices such as cover cropping and reduced-tillage and no-till farming (KM 11.1).[218,219] Combined with reduced tillage, cover cropping improves soil structure, organic carbon content, and infiltration and water-holding capacity in irrigated cropland[220] and positively impacts nutrient cycling, crop yield, and soil water conservation in limited-irrigation, semiarid cropping systems.[221,222] However, some farmers and ranchers, such as those who operate on small acreages, often find it hard to access the resources to transition practices or may perceive the risks of change to be too great, including financial expense and the perceived need to learn new skills.[223]

Irrigation efficiency can reduce risks to farming and ranching operations due to increasing temperatures, unreliable precipitation, and reduced water resources. However, access to these solutions can be complicated due to farm or ranch location, access to surface water and groundwater, water rights, current irrigation methods, and crop types.[224] In the Verde Valley of Arizona, limited access to materials, equipment, and financial resources, especially for small-scale producers, inhibits their ability to respond to water-related challenges.[224] Indigenous Peoples face barriers in accessing support from the Natural Resources Conservation Service (NRCS) related to land tenure, financial assistance, institutional mismatches, and complexities in incorporating Indigenous agricultural methods in applications for NRCS programs.[225,226]

## Key Message 28.4

## Climate Change Compromises Human Health and Reshapes Demographics

Increases in extreme heat, drought, flooding, and wildfire activity are negatively impacting the physical health of Southwest residents (*high confidence*). Climate change is also shaping the demographics of the region by spurring the migration of people from Central America to the Southwest (*medium confidence*). Individuals particularly vulnerable to increasing climate change impacts include older adults, outdoor workers, and people with low income (*high confidence*). Local, state, and federal adaptation initiatives are working to respond to these impacts (*high confidence*).

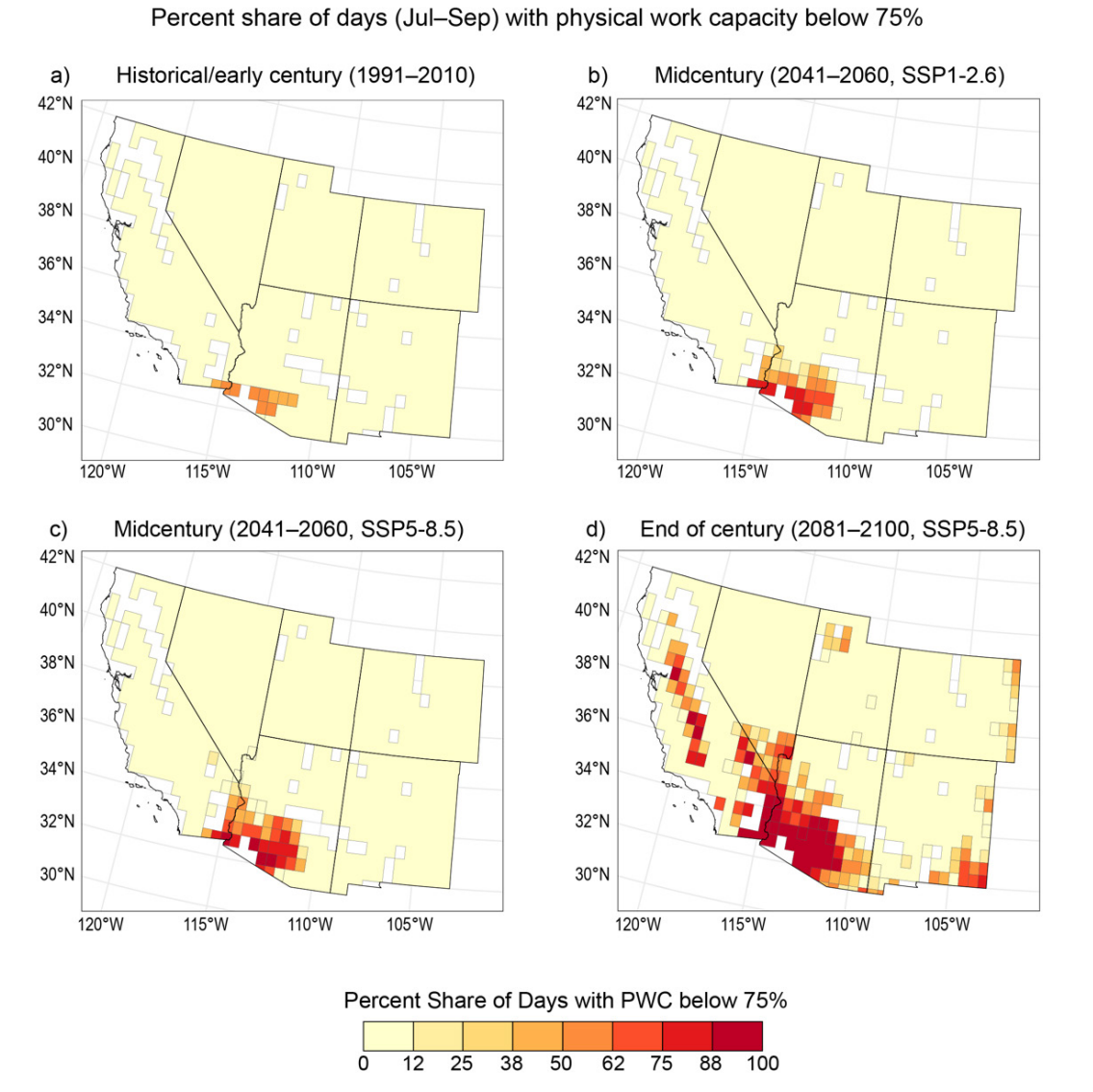
### *Extreme Heat Impacts*

Since 2018, 31 large climate- and weather-related disasters have affected the Southwest, resulting in more than 700 fatalities and estimated damages totaling $67.3 billion (in 2022 dollars).[2] Strong evidence indicates that extreme heat disproportionately impacts the health of frontline and overburdened communities in the region (KM 15.2), including the unhoused,[227,228,229] outdoor workers, and migrant farmworkers (Figure 28.7; KM 11.2),[230,231,232,233] as well as those with low income[8,234] and older adults.[235] Between 2016 and 2020, 7,687 hospitalizations in the Southwest were due to heat and heat-related illnesses, in comparison to 5,517 in the previous five years (2011 to 2015).[236] Pre- and post-natal exposure to high heat and air pollution are shown to be particularly dangerous in the region.[237,238,239,240]

Extreme heat and high-ozone days in the region are expected to increase under climate change (KMs 2.3, 3.5).[241] These changes are expected to increase heat and air-pollution exposure, illness, and premature death.[242] Intensified aridity from higher temperatures and drought is expected to lead to more dust storms[243] and more than double the number of deaths attributed to fine dust by 2080–2099 under a very high scenario (RCP8.5), relative to 1986–2005 (KM 6.1),[244] with increasing exposures for outdoor workers during the warm season. The incidence of coccidioidomycosis (Valley fever) in the region has increased (Figure 15.2)[245] and is associated with higher air temperatures and drier soils,[246,247] with greater risk to those whose job requires dirt disruption. The annual average cost to the US economy of Valley fever for the 2000–2015 baseline was $4.8 billion per year (in 2022 dollars), which is projected to increase 390% by 2090 under a very high scenario (RCP8.5; Figure 15.2).[248]

Extreme heat exposure also affects the economy through decreased productivity and well-being in outdoor workers (Figure 28.7),[249,250,251] especially among migrant agriculture workers in the region (KM 15.1).[252,253] Impact estimates to productivity provided in Figure 28.7 are projected to result in a loss of 25% of the workday on all days in the third quarter (July–September) under a very high scenario (SSP5-8.5) by the end of century and cause important losses to the economy (KM 19.1). Dehydration due to working outdoors in extreme heat in California is linked to acute kidney illness even after a single day of exposure.[254] Research into the mechanisms of chronic kidney disease related to climate change is ongoing, yet occupational heat exposure is a causal factor.[255]

## Heat Impacts in the Southwest




**With extreme heat events expected to increase in frequency and severity, the ability to perform work outside is projected to decline across parts of the Southwest.**

**Figure 28.7.** The ability to perform work outside—as measured by physical work capacity (PWC)—will decline across large swaths of the Southwest due to heat exposure throughout the century, with the greatest declines expected in southwest Arizona, southeast California, and California's Central Valley. These impacts on outdoor work will affect agricultural output, as well as earning ability for workers. PWC has a range of 100% (no loss of work capacity) to 0% (complete loss). The maps display the proportion of days in the third quarter (July to September) in which PWC is less than 75%. In historical conditions (**a**), a few locations in southern Arizona had PWC values less than 75% for half of the quarter. (**d**) Under a very high scenario (SSP5-8.5) by end of century, most of southern Arizona, southeast California, and some of California's Central Valley are projected to have less than 75% work capacity for all days in the third quarter. This daily labor loss is calculated based on a given heat load (temperature, humidity, and solar radiation) compared to temperate conditions where there is no thermal effect on work output. To provide a full range of potential impacts, maps are based on representative years for (a) historical/early century (1991–2010); (**b**) midcentury (2041–2060, SSP1-2.6 [low scenario]); (**c**) midcentury (2041–2060, SSP5-8.5 [very high scenario]); and (d) end of century (2081–2100, SSP5-8.5). Estimates are based on an individual performing moderate to heavy agricultural work outdoors over a daytime shift (about 7 hours). The PWC is an empirical estimate based on human physiological chamber studies quantifying how PWC changes with the environment heat load based on the wet-bulb globe temperature.[256,257,258,259] Land areas in white had no crops in the early 21st century. Figure credit: University of Illinois–Urbana Champaign and Arizona State University.

## Air Quality and Health Impacts

While the annual average level of fine particulate matter ($PM_{2.5}$) has seen decadal decline in the region due to strengthened air quality policies reducing emissions from controllable sources, disparities in $PM_{2.5}$ exposure and related health concerns remain high in the region.[260] Moreover, the frequency and severity of smoke events with $PM_{2.5}$ exceedances of federal air quality standards have increased significantly due to wildfires (Figure 14.3). Since 2015 in Northern California, the annual average $PM_{2.5}$ has increased because of wildfire events, which have taken over as the main source of $PM_{2.5}$ exceedances.[261] $PM_{2.5}$ in wildfire smoke contributes to adverse health effects for firefighters[262] and the public[263,264] and can be more hazardous to health than similar levels of particulates from other sources.[265] The costs of adverse respiratory and cardiovascular health outcomes can exceed the billions spent on wildfire suppression (KM 28.5).[266] Chemicals in wildfire smoke also correlate with increased cancer risk.[267] Direct exposure to the 2018 Camp Fire in California has been linked to mental health disorders such as depression and post-traumatic stress disorder.[268] Wildfires can also cause other public health impacts, including water contamination when fires damage water distribution infrastructure,[269] long-term loss of access to clean drinking water,[270] and increased landslide risks (KM 28.5).

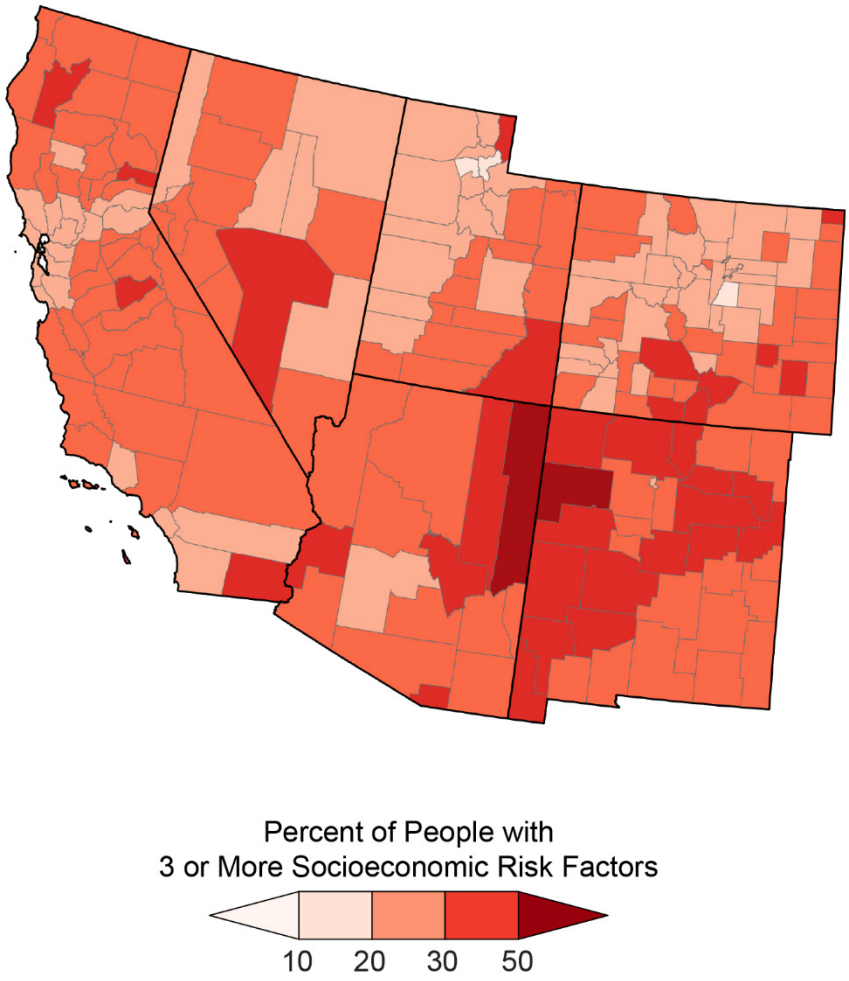
## Flooding and Disease

Increases in flooding in the region are projected with continued warming.[271,272] These changes increase risks of water-borne diseases and exposure to toxic hazards and place stress on food, energy, and water supplies, as well as farmworkers' health (including interconnected sectors) and their socioeconomic insecurity.[39] Flooding exposures may increase as a greater proportion of the population across the region, on average, is living on 100-year floodplains (e.g., in California, between 1990 and 2020, 25,000 more people lived on 100-year floodplains).[137] Flooding can also interrupt vector-control programs, such as for West Nile virus.[273] The region is seeing challenges with West Nile virus, particularly in Arizona and California,[274] with projected increases due to changes in the climate, human population, and mosquito distribution (KM 24.3).[275,276]

## Impacts to Outdoor Workers

Limited occupational health and safety standards for farmworkers and other outdoor workers are of key concern, as intensifying wildfires and heat collide with harvest season each year, particularly for undocumented Latino/a and Indigenous migrants.[231] The improvement of these standards at the state and national levels will be critical for health adaptation to climate impacts in the region. Moreover, the harm to farmworkers due to wildfire smoke is expected to be greater than previously thought, bolstering the argument for additional research and policies to help safeguard overburdened and stigmatized populations.[277] Many Southwest cities experienced high rates of economic and population growth during the second half of the 20th century, particularly between 2015 and 2019.[31] The region's flourishing economy and proximity to the Mexican border result in a high influx of migrants.[278,279] Migrants from Central America, spurred to migrate due to climate change in addition to poverty and violence (KM 17.2), are drawn by the Southwest's strong economy and increase the number of vulnerable people and change the demographics in the region. Local, state, and federal efforts to both mitigate climate change and support essential human adaptation to increasing exposures will be vital in protecting the health of a growing and aging population and our most vulnerable communities (Figure 28.8; KM 15.1).[280]

### Community Resilience Estimates for the Southwest




**Communities with higher socioeconomic risk factors are expected to be less resilient in the event of climate and weather disasters.**

**Figure 28.8.** The map shows community resilience estimates (CREs) for the Southwest. Community resilience is the capacity of individuals and households to absorb, endure, and recover from the health, social, and economic impacts of a disaster. Individual and household characteristics from the 2019 American Community Survey were modeled, in combination with data from the Population Estimates Program, to create the CREs at the county level. Darker shading indicates a higher proportion of the population at risk. Adapted from US Census Bureau 2021.[281]

## *Demographic Shifts Related to Climate*

The effects of climate change on other regions of the world—especially Central America—are changing the Southwest's demographics. Decreasing agricultural productivity, increasing levels of food insecurity, and adverse climate effects are among the main reasons why people emigrate from the Northern Triangle (Guatemala, Honduras, and El Salvador) to the US (KM 17.2).[32,279] In 2021, 42% of Central American immigrants to the US lived in the Southwest region,[282] and about 43% of immigrants apprehended at the Southwest border in 2019 originated from the Northern Triangle.[278] Many are poor, women, children, or Indigenous Peoples. Climate-related migration has been shown to affect people's physical and mental health, resulting from exposure to weather extremes, disruption of social ties, and overcrowding of health systems in the host communities.[283]

### *Adaptation Efforts for Health*

Several programs have been developed to address the health impacts of climate change in the region, but financial constraints and political support affect their implementation.[284] Since 2010, the CDC's Building Resilience Against Climate Effects program in Arizona and California has developed and implemented strategies to protect communities from climate-sensitive hazards, including schools, healthcare facilities, and other at-risk populations.[285] This program, currently in 10 cities across the country, has developed important resources and programs that can be scaled up for future climate resilience efforts. To protect the health and learning of school children, the Arizona Department of Health Services created new heat policy guidance, resulting in recommendations for school heat safety and adaptation strategies.[286,287] In California, San Mateo County assessed asthma burden connected to local climate issues.[288] Public health guidance in the region should focus on co-exposures to heat and wildfire smoke in adaptation efforts,[289] particularly given the projected increase in childhood asthma due to wildfires.[290] While data on private sector investment is limited, the private sector has historically lacked incentives to invest in adaptation (KM 31.6). Globally, in 2017–2018 only 1.6% of all adaptation financing came from the private sector.[291] In the Southwest, however, certain sectors, such as insurance, came under pressure from the local authorities to get involved in tackling climate change by divesting their fossil fuel–based investments.[292]

## Key Message 28.5

## Changes in Wildfire Patterns Pose Challenges for Southwest Residents and Ecosystems

In recent years, the Southwest has experienced unprecedented wildfire events, driven in part by climate change (*high confidence*). Fires in the region have become larger and more severe (*high confidence*). High-severity wildfires are expected to continue in coming years, placing the people, economies, ecosystems, and water resources of the region at considerable risk (*very likely, high confidence*). Opportunities for adaptation include pre- and postfire actions that reduce wildfire risk and facilitate ecosystem restoration and include traditional land stewardship practices (*high confidence*) and the application of Indigenous cultural fire (*medium confidence*).

Fire is a natural process in many ecosystems across the Southwest and is necessary for biodiversity, ecosystem services, and nature-based solutions (KM 8.2). Fire regimes associated with fire-dependent ecosystems are highly variable with elevation and across geographies.[293] Long-standing policies and forest management—including fire suppression, widespread logging and livestock grazing, and elimination of Indigenous fire use—combined with the effects of a changing climate, have contributed to high tree densities, compromised ecosystem function, and the diversity, or heterogeneity, of forest attributes such as species, size classes, and geographic distributions.[18,21,294,295,296] Consequently, many Southwest forests and fire-prone wildlands are susceptible to climate-mediated impacts including droughts, pests and disease (Box 7.1), and devastating wildfire.[295,297] An abundance of scientific research strongly suggests that Southwest ecosystems, in the face of rapid climate change–induced transformation, will require active management interventions that increase forest heterogeneity and enhance ecosystem function and adaptive capacity (KM 7.3).[298,299,300]

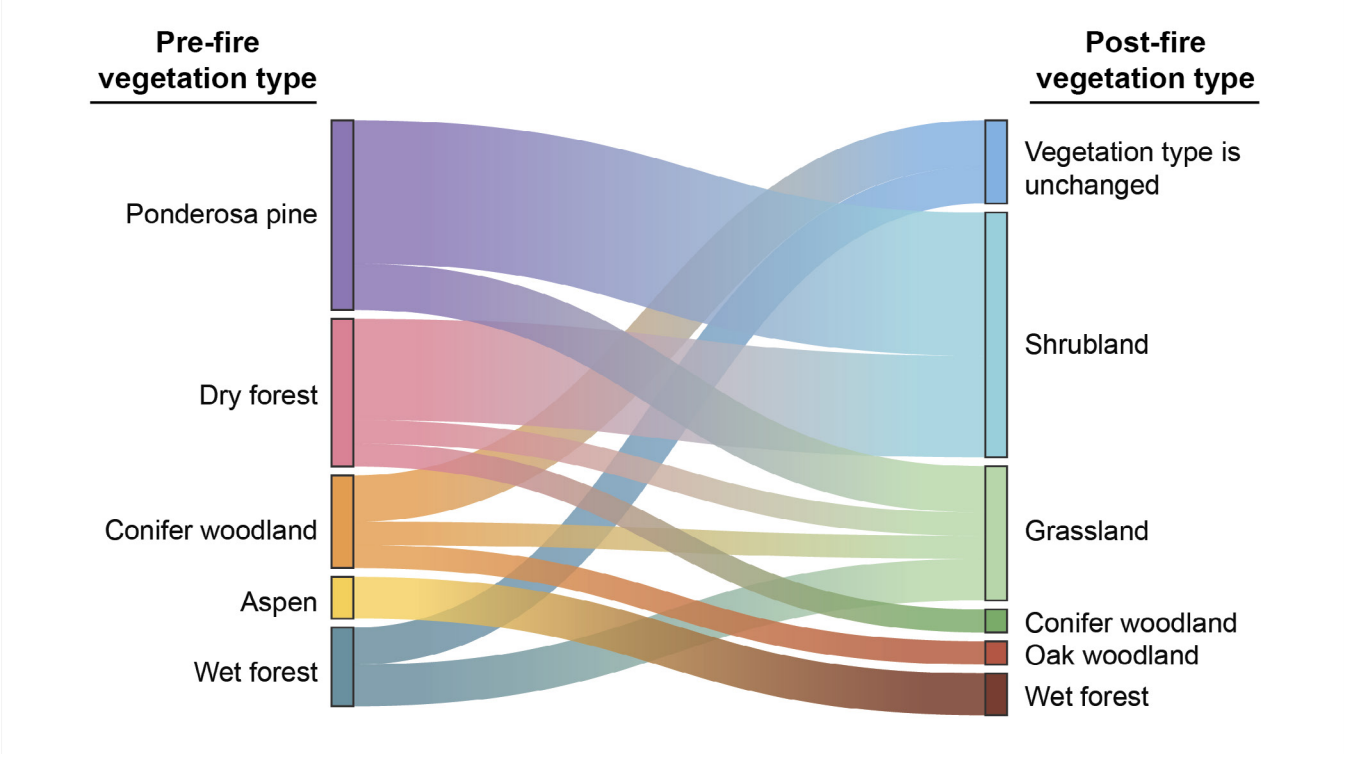
Human-induced warming temperature trends, changes in precipitation patterns, and increases in vapor pressure deficit have driven the desiccation of fuels that influence wildfire patterns and behavior across the western US (KM 7.1).[17,18,19,20,21,301] In the Southwest, fires have become larger, more frequent, and, in many

areas, more severe (KM 7.1), with clear evidence of climate change as a major cause.[302,303] Seven of the ten largest US wildfires in 2020–2021 occurred in the region. Of the 50 largest US wildfires in 2020, 22 occurred in California, and the 7 largest wildfires recorded in California have occurred since 2018.[304,305,306] The three largest wildfires recorded in Colorado occurred in 2020; the largest fires in Nevada history burned in 2018;[307] and the largest wildfires in Arizona, New Mexico, and Utah all occurred since 2007 (Figure 28.9; Focus on Western Wildfires). Large fires on non-forested western US rangelands also increased more than fivefold during the period 1984–2017.[308] Much of this increase is driven by increases in invasive annual grass cover, caused partly by climate change and increased atmospheric carbon dioxide.[309]

## *Impacts on Ecosystems*

Climate change causes cascading effects with other factors in Southwest ecosystems that are otherwise fire-adapted. For example, large areas of high-severity fire have driven ecosystem type conversions in many parts of the region.[294,310] Semiarid to arid forest systems are particularly vulnerable to these effects and have experienced conversion to native grassland,[311] shrubland, or non-native grassland (Figures 28.9, 8.6).[294] The cumulative effects of fire-driven ecosystem changes continue to place ecosystems at high risk of vegetation type conversion (e.g., forests to shrublands), which can result in severe impacts on watersheds and aquatic resources.[294] Effects include degradation of riparian systems; risks to riparian and riverine species, as well as to threatened and endangered species, from erosion caused by extreme precipitation events; and increased invasions by non-native species.[312]

### Wildfire and Vegetation Change in the Southwest




**Climate change is leading to larger and hotter fires and resulting in shifts in vegetation.**

**Figure 28.9.** Data from the states of California, Arizona, Colorado, and New Mexico show that approximately half (about 50%) of vegetation type change (e.g., forests transiting to shrublands or grasslands) is a function of high-severity fire. Adapted from Guiterman et al. 2022[294] [CC BY 4.0].

Recent climate-induced aridification, including loss of snowpack, has also hindered postfire tree seedling and shrub establishment, limiting ecosystem recovery.[313,314,315] This is particularly true of postfire conditions for water availability, quantity, and quality. Moreover, interactions between wildfire and natural drought variability are expected to increasingly exacerbate dry conditions that will further stress tree seedlings[316] and drive potential future shifts in species composition or vegetation type.[314,317] Conversions of coastal shrublands driven by human development also have interacted with climate-induced drying of vegetative fuels to generate atypical fire conditions.[318]

Projections of future climate change suggest that wildfire activity will continue to affect ecosystems and their services.[298,319,320,321,322] Specific ecosystem responses to climatic changes will depend on interactions among vegetation type, moisture stress, disturbance regimes (e.g., pests, pathogens, and high-severity fire), and human land-use changes (KM 6.2).[295,297,319] For example, climate change is predicted to lead to a loss of sagebrush ecosystems in the southern and eastern Great Basin because those ecosystems are less able to recover after fires in a warmer, drier climate.[323]

However, future wildfire trends are less certain in rangelands than in forests because fire size (measured by annual area burned) and severity (a shift from low-intensity fires to stand-replacing crown fires) depend on production of aboveground vegetation that varies annually with climatic conditions.[324] Growth of the grasses that typically fuel wildfires is expected to decrease in Arizona and New Mexico,[199,325] whereas elsewhere in the region, precipitation is projected to increase early in the growing season, which, when followed by hotter summers, will generate conditions ideal for fire ignitions.[324]

## *Impacts on People and Communities*

Climate-related increases in the frequency, severity, and extent of wildfires in the Southwest are endangering lives and property (Focus on Western Wildfires).[17,18,19,20,21,326] Complete data across the region on wildfire-caused fatalities are sparse,[327] but three of the five deadliest fires on record in California have occurred since 2017, costing 122 lives.[304] Further, loss of life can be attributed to wildfire smoke, which has also been linked to increases in COVID-19 fatalities in Northern California[328] and postfire debris flows that can leave slopes bare of vegetation and vulnerable to rapid erosion (Ch. 7; Focus on Western Wildfires).[329] The risk of postfire debris flows in coastal communities is expected to increase due to an increase in heavy precipitation typically delivered by atmospheric river events (KMs 28.1, 8.1).[330]

Property losses due to wildfire are greatest in the Southwest compared to other regions. In 2021, 3,363 structures burned due to wildfires in California, the highest number lost in any state, while the December 2021 Marshall Fire in Colorado, a fast-burning grassland fire, burned more than 1,000 homes in just a few hours.[306] The 2022 Calf Canyon/Hermit's Peak Fire that burned 341,735 acres is New Mexico's largest fire. Secondary impacts of wildfire, such as postfire debris flows (Figures 3.13, 6.5) on recently burned slopes, impose additional hazards to property.[329] The estimated cost of fighting the 10 largest California wildfires in 2021 exceeded $2.25 billion (in 2022 dollars),[306] with suppression costs representing only a fraction of a total economic impact that also includes loss of structures and infrastructure, increased medical costs, crop losses, water quality contamination, and other factors (KM 19.1).

The increase in structures and infrastructure lost can be linked to population growth in the wildland–urban interface (WUI; Figure A4.14), where houses are built close to forests and other natural areas.[331] The number of Americans living in the WUI doubled from 1990 to 2010, and the WUI population has risen fastest in areas such as the Southwest where wildfire risk is greatest.[332,333] While migration to WUI counties shows modest reductions immediately after wildfire or extreme heat events,[334] fires do not seem to drive current residents away; fewer than 6% of Sonoma County, California, residents who lost homes to wildfires in 2017 subsequently left the county.[335]

Impacts of fire on community livelihoods depend on exposure to wildfire risk and capacity to adapt (KM 7.3). Analysis of livelihood vulnerability in 14 fire-prone states found that New Mexico and Arizona residents were most vulnerable due to relatively high risk exposure and low to moderate access to resources needed to adapt to changing conditions.[336] Low-income areas, communities of color, undocumented Indigenous migrants, sexual and gender minorities (KM 15.2),[337] and unsheltered persons are most vulnerable to wildfire impacts,[231,338] including water contamination from carcinogenic compounds.[269] Populations with medical disabilities or limited mobility, older adults, and those who rely on medical equipment are also disproportionately at high risk during wildfires.[339]

Wildfires, moreover, often occur during farm harvest seasons, increasing health risks for workers.[277] Southwest industries especially vulnerable to wildfires include wineries,[340] tourism,[341,342] forest products,[183] and legal cannabis cultivation.[343] For example, in the 2020 fires, the economic impact of smoke taint is estimated to have cost the California wine industry $4.2 billion (in 2022 dollars). Smoke taint occurs when smoke and ash permeate the skin of grapes and can affect the taste and smell of wine.[344]

Impacts of wildfire on natural environments can affect ecosystem services (KM 7.2) that people derive from those environments, including air quality (KM 28.4),[266] water quality and availability,[345] pollination,[346] livestock forage and health,[347] and outdoor recreation.[348] Ecosystem service effects vary over time as short-term declines in services can be followed by improvement over a longer term as ecosystems recover.[349] Wildfires in forested ecosystems chemically alter watersheds and can reduce drinking water quality,[350] in some cases leading municipalities to issue drinking water advisories.[351] Postfire hazards such as floods and debris flows further threaten water security (Focus on Western Wildfires).[352] Smoke from the 2020 wildfires significantly reduced industrial solar energy production in Southern California.[353]

While high-severity wildfires (i.e., stand-replacing fire) generally have negative impacts, wildfires and prescribed fires that burn at low to moderate severities can have positive effects by reducing fuel loads, curtailing plant pests and diseases, and stimulating new vegetation growth.[354] Prescribed burning, while an effective tool to reverse undesirable changes in forest vegetation structure due to fire suppression, can also reduce air quality in the short term.[266]

## *Ecosystem Management Challenges and Adaptation Solutions*

Forest resilience may be enhanced by thinning trees, leveraging low- and moderate-severity wildfires with traditional forest management treatments that adjust fuels, and better incorporating managed wildfire.[299] Using prescribed fire in conjunction with mechanical forest treatments, such as thinning or pruning, also reduces tree densities and fuels.[300] Prescribed fire can increase forest resilience during periods of climate-related stress, such as sustained drought,[355] and can reduce the extent and intensity of the wildfire regime.[356] Cultural fire use to meet Indigenous and Tribal objectives can be compatible with traditional fire application and help advance increased resilience to climate change.[296,357]

To decrease competition for water resources and increase forest resilience, reductions in tree density and fuels can lower the risk of high-severity wildfires and drought- and pest-induced mortality (KM 6.2).[358,359] Recent evidence suggests that increasing these approaches can help adapt to the rapidly increasing risks.[299,360] However, the implementation of prescribed fire may be curtailed due to public concerns about smoke and fires that escape management prescription.[361]

Natural lands, including forests and associated woodlands, play a central role in mitigating climate change (KM 32.1).[362,363] However, climate variability, drought- and pest-driven tree mortality, wildfire, and other disturbances suggest that the Southwest will see a continued decline in terrestrial carbon storage.[362,364] As a result, securing or even increasing ecosystem carbon storage is often an objective for forest management investment.[365] Forest management treatments differ in their short-term carbon losses relative to the

expected benefits of greater fire resistance, which leads to longer-term carbon stability (Box 7.2). In Southwest forests, reducing thinning area and increasing the area burned enhances the potential for a net carbon benefit when compared to no action.[366] Reforesting areas where forest cover was lost due to mortality can help mitigate the effects of climate change,[367] but planting additional trees that increase forest density would result in elevated fire risk and drought stress and therefore is not expected be an effective adaptation solution.[300,368]

Other adaptation solutions include power shutoff policies by utilities to reduce wildfire risk when extreme wind events are predicted to topple powerlines and telecommunications infrastructure.[369,370,371] Power shutoffs are more likely in autumn due to a climate-related increase in the number of days with extreme fire weather.[18] Power shutoffs may also increase homeowners' intention to adopt solar power[372] or fossil fuel–powered generators.[373] Individuals who experienced shutoffs reported poorer physical and mental health immediately after the occurrence, yet they still supported the use of shutoffs as a wildfire risk-reduction strategy.[374]

# Traceable Accounts

## *Process Description*

Following their selection in August 2021, the chapter lead author, federal coordinating lead author, and agency chapter lead author developed a comprehensive list of author candidates based on an analysis of prior National Climate Assessments, published scientific literature, science communication outlets, and policy-relevant reports. The final chapter authors were then selected based on their depth of knowledge, diversity of expertise, and experience in issues critical to the Southwest. Furthermore, authors were selected to represent diverse perspectives in terms of race, ethnicity, and gender identity. The Southwest chapter public engagement workshop was held virtually on February 4, 2022, with more than 90 participants. The workshop included an overview, a series of breakout rooms where the participants provided feedback on key topics, and a final roundup discussion among all participants. The author team held a debriefing session on February 7, 2022, to reflect on the input provided during the workshop. The author team met weekly during the development of the chapter.

Based on discussions among the author team, input from stakeholders, and consideration of the Fourth National Climate Assessment, the authors developed five Key Messages representing the valued assets and unique characteristics of the region. These include water resources, the coast, food and agriculture, demographics and human health, and wildfire. The chapter details the observed and anticipated effects of climate change on human and natural systems across those topics and outcomes to be avoided in the absence of adaptation and mitigation.

For the scientific assessment, the authors conducted a systematic evaluation of the body of scientific and technical knowledge to synthesize published studies, data, models, and assumptions while applying best professional judgment to assess uncertainties and conflicting findings. The chapter pays specific attention to factors that make specific systems and groups more vulnerable. The chapter identifies intersections between topics, cascading risks, and paths to resilience. The chapter also addresses cross-cutting themes including adaptation solutions and challenges, climate change equity and environmental justice, Indigenous Peoples and Knowledges, economics, infrastructure, and ecosystems and ecosystem services.

## Key Message 28.1

## Drought and Increasing Aridity Threaten Water Resources

### Description of Evidence Base

Instrumental data and paleoclimate data provide strong, abundant evidence that the early-21st-century drought in the Southwest is more severe than most, but not all, prior drought periods.[28,45,46,375] Research has identified higher temperatures as being a major driver of drought severity through the mechanism of increased atmospheric demand.[47] Recent research builds on an already-substantial evidence base demonstrating the decline of southwestern snowpacks over the last century.[5,6,49,50] Research has shown how drought-induced shortages in surface water have increased groundwater pumping in California's Central Valley,[67] which provides one example of how drought may reduce future water access, especially if aquifer recharge is also reduced.[63]

### Major Uncertainties and Research Gaps

Historical data supply insight into the potential impact of precipitation deficits on surface water, and various research studies demonstrate how precipitation deficit and higher rates of evapotranspiration feed into reduced soil moisture and infiltration, both in contemporary and future warmer climates. However, there is remaining uncertainty over the precise contribution of temperature to these declines in 20th-century

Upper Colorado streamflow,[375] the impact of changing snowpack dynamics on streamflow in and across different southwestern river basins,[56] and the impacts of El Niño–Southern Oscillation on precipitation in the region.[376,377]

There are also research gaps on the impacts of climate change on the full hydrologic cycle of the Southwest. From the biophysical perspective, there's a lack of information about aquifer recharge, specifically regarding temporal variability of recharge rates and locations.[63] Another topic for further exploration is the relationship between drought, surface water supplies, and rates of groundwater pumping for agriculture in locations within the Southwest beyond California (e.g., Rio Grande and tributaries, Utah, Nevada). Further, there is limited research on climate change impacts on the dynamics of the North American Monsoon, including how to more effectively capture monsoon moisture to substitute for decreased winter precipitation, as well as on other extreme precipitation events such as atmospheric rivers.

Additionally, there are multiple paths for water adaptation in the Southwest for industry, agriculture, and communities to build resilience to a more water-scarce future. However, there are research gaps around the feasibility and long-term effects of these adaptation solutions.[378,379] Moreover, the ability of different sectors and communities—including rural, low-income, Indigenous, and other frontline communities—to adapt to climate-induced water scarcity is highly variable across the Southwest.[380] There is a gap in research on best practices to support these communities in adapting to current and future water scarcity.

Currently, Indigenous Peoples' water rights are under-utilized, while water access remains a challenge for many Indigenous Peoples. As more Indigenous Peoples gain access to and use their water rights, there is limited research on how this might impact other water users and broader water management actions, especially under Colorado River drought policies.[381]

## Description of Confidence and Likelihood

Measurements of snowpack, streamflow, and groundwater over the last century support the observation, with *very high confidence*, that climate change has reduced surface water and groundwater availability for people and nature in the Southwest.[4,14,56] Moreover, evidence from the peer-reviewed literature supports the assertion of *high confidence* that certain Indigenous and frontline communities, including agriculturalists, will experience disproportionate impacts from reduced water availability and that long-standing institutional frameworks drive these inequities.[187,382,383,384]

The *high confidence* that higher temperatures have intensified drought and will *very likely* lead to a more arid future is based on recent evidence that shows that since the early 20th century higher temperatures have increased the proportion of precipitation being lost to evapotranspiration relative to its contribution to Colorado River flow—a trend that is expected to continue as the region warms.[28,51]

Without extensive adaptation, which is challenging because human systems have developed under the historical water cycle patterns (KM 4.2), there is *high confidence* and it is *likely* that these dynamics will further stress existing water supply–demand imbalances. Water supply imbalances primarily refer to the over-allocation of surface water supplies in the region's major rivers, such as the Colorado and Rio Grande, due to committing more water to what are legally known as "beneficial uses" than is currently available. Concurrently, longitudinal studies and climate models suggest that there is *high confidence* that increased flooding will occur due to more intense precipitation events, such as those caused by atmospheric rivers,[71,72] in the region's future.

There is *medium confidence* that flexible and adaptive approaches to water management have the potential to address changing climate risks and mitigate the impacts on people, the environment, and the economy (KM 4.3). While there are abundant examples of such approaches from around the world and in multiple water-use sectors, assessments of the feasibility of these examples in the Southwest are lacking.

## Key Message 28.2

# Adaptation Efforts Increase to Address Accelerating Impacts to the Region's Coast and Ocean

### Description of Evidence Base

Recent research and observed events demonstrate that marine heatwave events will continue and increase in frequency alongside other stressors, impacting marine-resource dependent communities.[35,95] Marine heatwaves and century-scale sea surface temperature warming trends near the coast of California have been attributed to human influence on climate.[385] Adverse impacts to aquaculture and wild-capture fisheries have already been observed and are projected to worsen. Impacts are connected to the degradation of marine ecosystems from not only temperature effects but also ocean acidification, hypoxia, and harmful algal blooms. And while there is extensive literature on the California Current ecosystem and wild-capture fisheries, there are fewer studies on the long-term effects of extreme events and California aquaculture, and thus higher uncertainty.

Sea level rise impacts have been extensively modeled and compared with observed flooding. The most recent lines of evidence are synthesized with a large body of relevant literature included in the 2022 Interagency Task Force report on sea level rise[7] and the Intergovernmental Panel on Climate Change Sixth Assessment Report from Working Group I.[95]

The authors focused on findings on the impacts from sea level rise, which centered around new understandings of sea level rise impacts to groundwater and infrastructure and communities. Energy and transportation infrastructure will continue to be impacted by increased flooding. Furthermore, recent studies have shown that climate impacts will disproportionately impact overburdened communities, but additional research specific to California is lacking.

Adaptation for infrastructure and communities has been accelerating in California through state and local governments, as seen through the release of laws, executive orders, and state guidance documents, as well as an increase in state, Tribal, local, and regional vulnerability assessments and adaptation plans. Government planning requirements and guidance for different sectors are increasing. The State of California also invests in downscaled climate science to inform state and local climate decision-making; the state's climate change assessment has been codified in law. Less information on adaptive strategies for fisheries and aquaculture has been released.

### Major Uncertainties and Research Gaps

Long-term, compound implications of greater extremes with other stressors and mitigation strategies are less certain. There is less research in California on combined, long-term impacts of marine heatwaves and multi-stressor effects on ecosystems, species, and aquaculture. However, multi-stressor research is advancing,[386] including for the California Current,[387] increasing our mechanistic understanding of climate change effects. Mitigation strategies of nature-based carbon dioxide removal are growing in interest and investment in the US (Ch. 32),[388] including in California. While the emerging evidence suggests that ocean-based solutions, such as seaweed aquaculture carbon sequestration, are not a global "silver bullet" to mitigate carbon emissions, they may provide some local benefits.[133] However, who benefits from such interventions and the impacts to surrounding ecosystems require further investigation to ensure positive outcomes for nature and people.[389,390,391]

There is a lack of research on the impacts of sea level rise on groundwater flooding, as well as the application of those findings to infrastructure and community analyses. These compounding threats

have not been included in most adaptation planning to date, which could result in less adaptive solutions being implemented.

As governments and communities begin building adaptation projects, uncertainties about their efficacy remain. There is limited research tracking adaptation implementation, including research identifying potential ramifications, such as displacement of overburdened communities, economic injustices in terms of resources available for adaptation, and methods to ensure communities are part of decision-making for eventual retreat or relocation. Additional work could help identify how existing funding tools can support adaptation and resilience efforts and how to develop a more robust understanding of adaptation costs and benefits.

## Description of Confidence and Likelihood

There is *high confidence* that climate change will increase marine heatwaves and harmful algal blooms (HABs), resulting in impacts to coastal ecosystems and economies. There is *very high confidence* and it is *very likely* that marine heatwave frequency, intensity, and extent will increase. Laufkötter et al. (2020)[385] found that heatwaves have already increased twentyfold because of human-caused global warming and that the probability of occurrences increases in frequency under progressively warmer scenarios. Linkages between HABs and thermal conditions of the oceans have been demonstrated, but frequency and extent are linked to climate and non-climate (e.g., runoff) drivers.[392] There is high agreement and evidence of negative impacts to marine ecosystems and resource-dependent communities in the literature, but under moderate to high climate mitigation scenarios, the severity of impacts will depend on adaptative interventions (e.g., nature-based solutions, adoption of ecosystem-based management).

Sea level rise will *likely* cause increased flooding on the Southwest coast, and there is *very high confidence* that those impacts will severely affect infrastructure and communities, with inequities in how these impacts are experienced. The latest climate models and sea level rise projections demonstrate increased confidence in relative sea level rise amounts by 2050. Sweet et al. (2022)[7] state that relative sea level for the entire contiguous US coastline is expected to rise, on average, as much over the next 40 years (2020–2050) as it has over the last 100 years (1920–2020; 0.82–0.98 feet). Furthermore, by 2050 the expected relative sea level will impact tide and storm surge, leading to major and moderate high tide flood events occurring as frequently as minor high tide flood events occurred in 2022, which will impact infrastructure, communities, and ecosystems.[7]

Given the State of California's progress and leadership on climate science and adaptation planning for sea level rise, there is *high confidence* that adaptation planning and implementation will continue. As evidence, the state's fiscal year 2021–2022 budget included $4 billion (in 2022 dollars) for climate resilience programs, with other new climate resilience programs created in fiscal year 2022–2023. State agencies continue to release adaptation planning guidance (e.g., State Agency Sea Level Rise Action Plan 2022;[393] Extreme Heat Action Plan 2022;[394] State Adaptation Strategy 2021[395]) and new funding programs (e.g., Adaptation Planning Grant Program 2022;[396] Transportation Climate Adaptation Planning Grants 2022;[397] Local Transportation Infrastructure Climate Adaptation Project [LTCAP] Program 2022;[398] Regional Resilience Planning and Implementation Grant Program 2022[399]). There is limited to no inclusion of aquaculture in California state climate planning (e.g., Lester et al. 2022[400]), and comparatively less coverage overall in the scientific literature compared to wild capture and agriculture,[401] and thus there is *high confidence* that climate planning and adaptation solutions for aquaculture are less clear.

## Key Message 28.3

## Increasing Challenges Confront Food and Fiber Production in the Southwest

### Description of Evidence Base

Temperature and precipitation data clearly show that this century has been warmer and drier than the last.[50,381,402] This drying and warming trend is already resulting in measurable impacts on rangeland forage production,[403] dryland agriculture,[404] and irrigated crop yields. A substantial literature exists showing the impact of climate change on livestock production through changes in food quantity and quality, pests and disease, and animal health and well-being.[405] Evidence shows that climate is already affecting the distribution of livestock agriculture in the east of region. The Southern Plains (in New Mexico) and Central Plains (in Colorado) saw large decreases in cow numbers in the 2011–2014 drought.[406] Increasingly the Southwest's agricultural economy relies on crop production, but research anticipates downward trends in the production of numerous high-value crops in California[169] and reduced or less reliable supply of irrigation water that supports crop production throughout the region. Numerous examples of adaptation strategies exist, such as improved irrigation technologies, soil protection strategies, and shifts to Indigenous practices and crops, although there are barriers that inhibit widespread adoption of many of these practices.

### Major Uncertainties and Research Gaps

Southwestern food and fiber production is diverse, spanning rangeland livestock systems, irrigated croplands and orchards, dryland, and Indigenous farming. Each of these systems is nested within local, regional, and international contexts that can exacerbate or alleviate vulnerability to climate change. This diversity, combined with factors other than climate change (e.g., global pandemics, inflation, supply chains, access to financial support) contribute to the complexity of assessing the impacts of climate change on southwestern agriculture. There are therefore research gaps and some uncertainty on how the adaptation options described in the agronomic and range management literature can be applied in the real world.

Research gaps remain in our understanding of not only the biophysical and socioeconomic capacity to support change in southwestern agrosystems but also the will of farmers and policymakers to change the type of crops that are grown. For livestock producers who rely on forage from public lands, there is uncertainty about how climate change will affect the number of animals the land can support and how possible reductions in stocking rate will affect the viability of ranches and ranching-dependent communities.

### Description of Confidence and Likelihood

There is *high confidence* that continuing drought and water scarcity will make it more difficult to raise food and fiber in the Southwest without major shifts to new strategies and technologies. Climate models agree that the Southwest will continue to warm. This impacts the thermal tolerance and chilling requirements for economically important crops. There are multiple indicators that the Southwest is undergoing aridification; as a consequence, it is expected that there will be less available water for irrigated agriculture in the future.

Given substantive evidence in the literature, there is *high confidence*, and it is *likely*, that extreme heat events will continue to occur and are expected to worsen in intensity and increase in frequency in the 21st century.[167] Extreme heat reduces crop quality and yield[181,403] and affects livestock productivity (and in some cases survival), resulting in economic impacts.[197,198,405] USDA Risk Management Agency indemnities data from 1989 to 2021 show that heat events are already driving crop production losses across the region.

There is a growing literature that advocates for greater inclusion of Indigenous Knowledge for informing adaptation solutions in Southwest agriculture. There is *medium confidence* that Indigenous Knowledge, along with technological innovation, has the potential to inform sustainable agricultural practice

regionwide, as well as increasing Indigenous food sovereignty, because there are few studies to date that demonstrate how Indigenous Knowledge can be drawn on to adapt larger acreages or commercial operations to climate change. It is also evident in the literature that technical innovations (e.g., agrivoltaics, internet of things) have yet to become more widely adopted or applied to larger acreage operations.

## Key Message 28.4

## Climate Change Compromises Human Health and Reshapes Demographics

### Description of Evidence Base

Strong evidence and good agreement among multiple sources and lines of evidence show that extreme heat exposures already are leading to heat-associated deaths and illnesses across the region.[228,233,407] Exposures to extreme heat for city dwellers are increasing, partly due to human-caused climate change and partly due to urban-induced warming.[408,409] Regional-scale warming in the Southwest since 1901 exceeds what would be expected from natural variability and is partly attributable to human influence.[3] Climate change has doubled the likelihood of an event capable of producing catastrophic flooding for California, and future increases to this risk are expected due to continued warming.[271,272]

Multiple lines of evidence indicate current and future increases in human exposures and adverse health outcomes to wildfire smoke in the region.[277,410,411] Good agreement exists among models that the intensified arid conditions in the region will result in more dust storms[243] and thus a higher incidence of respiratory ailments, including Valley fever.[246,248]

Evidence supports the need for increased investments in adaptative strategies that support social, physical, and health systems that enhance individual and community resilience to changes in climate, particularly extreme heat.[288,412,413,414,415] Improving public health systems and community infrastructure in the region can reduce the health consequences of climate change.

### Major Uncertainties and Research Gaps

Uncertainties exist in the attribution of changes in climate variables to specific health outcomes. The collection of and alignment of more environmental and health data will assist in understanding the long-term nature of how climate change affects specific health outcomes. Detecting direct relationships between climate change impacts and public health outcomes is also made more difficult due to confounding factors related to socioeconomics, vulnerability, exposure assessments, demographic shifts, migration, and community and individual characteristics. Detection and attribution studies are thus vital to the region for addressing multiple public health concerns (e.g., Ebi et al. 2020[30]).

Related uncertainties in how regional changes in climate will affect public health exist due to variability in projections of extreme precipitation; uncertainties in the occurrence and intensity of climate-sensitive exposures that impact human health, including wildfire smoke exposures; and variability in local and regional ozone based on meteorological conditions and emissions-reduction targets achieved.

Uncertainties also exist in projecting climate-related changes to the abundance of vector-borne diseases and associated disruptions. While US rates of chikungunya and Zika dropped[416] with widespread travel restrictions due to COVID-19, issues with West Nile virus (WNV) remain due to the endemic nature of the virus in the region. The most common WNV vector in the region (*Culex quinquefasciatus*) is abundant in urbans areas such as Los Angeles, Albuquerque, and Phoenix,[417] and certain water management structures (e.g., catch basins, storm drains, and retention ponds) provide favorable environments for *Cx. quinquefasciatus* reproduction.[418] There is also uncertainty around how heavy precipitation, as compared to drought

conditions, impacts the abundance and distribution of vector-borne diseases connected to human activity and management of water. Transmission of WNV is also projected to shift northward,[419] thus decreasing potential risks of transmission in parts of the Southwest.

Finally, considerable uncertainties exist in how individuals and communities will adapt to the effects of climate change in the region. Model projections of health impacts rarely account for adaptive capacity changes into the future. Improving adaptive capacity involves enhancing infrastructure, technologies, behavior, and the overall health of the population to cope with climate effects.

## Description of Confidence and Likelihood

There is *high confidence* that increases in extreme heat, drought, flooding, and wildfire activity are negatively impacting the physical health of Southwest residents. Climate models agree that the Southwest is experiencing higher temperatures and more intense, longer, and more frequent heat events.[3,8,375,420]Extreme heat exposure causes mortality, morbidity, and lost productivity if dangerous exposures occur (KM 15.2).[235,421] Drier conditions lead to a greater risk of wildfires and particulate matter, which adversely affect human respiratory and cardiovascular health when exposed.[265,290,422,423,424]

Climate change is also shaping the demographics of the region by spurring the migration of people to the Southwest, primarily from Central America (*medium confidence*). In 2021, about 13 million people (representing 21.3% of total population) living in the Southwest were foreign born; 21.1% of those foreign born entered the United States in the last 10 years.[425] Decreasing agricultural productivity, increasing levels of food insecurity, and adverse climate effects are among the main reasons why people emigrate from the Northern Triangle (Guatemala, Honduras, and El Salvador) to the US (KM 17.2).[32,279] About 43% of immigrants apprehended at the Southwest border in 2019 originated from the Northern Triangle.[278]

Individuals particularly vulnerable to increasing climate change impacts include older adults, outdoor workers, and people with low income (*high confidence*). Wildfires and the related smoke are affecting a higher number of people, with strong evidence pointing to the most vulnerable populations being at greatest risk.[426] Strong evidence further connects rising particulate matter levels to higher risk in already-vulnerable populations, including individuals with low income, Indigenous Peoples, pregnant people, children, and outdoor workers.[427,428,429,430,431] It has been well documented that extreme heat disproportionately impacts the health of the most vulnerable populations in the region, including the unhoused,[227,228,229] outdoor workers, and migrant farmworkers,[230,231,232,233] as well as people with low income,[8,234] older adults,[235] and pregnant people and babies (particularly with air pollution co-exposures).[237,238,239,240]

There is *high confidence* that local, state, and federal initiatives can respond to these climatic and demographic changes by helping people and communities become healthier and more resilient. There is strong evidence that increasing adaptive capacity and resilience across communities, especially the most vulnerable, will reduce the human health impacts of climate change.[432] The relative importance of various adaptive strategies will differ across spatial and temporal scales, climatology, and social and behavioral contexts. Improving public health systems, overall health, community infrastructure, and education can reduce health risks that are being exacerbated in the Southwest due to climate change, as well as many health risks in general.[431]

## Key Message 28.5

## Changes in Wildfire Patterns Pose Challenges for Southwest Residents and Ecosystems

### Description of Evidence Base

Changing wildfire dynamics include increases in wildfire size and severity and changing and lengthening fire seasons.[18,303,433,434] Extensive research has found that climate change is linked to increases in extreme fire weather,[18] wildfire activity,[20,303,326] wildfire severity,[17,19,21,434] and acreage burned annually.[302] Unprecedented high-severity fires have driven ecosystem conversions in many parts of the region.[294,311] Recent climate-induced aridification, including loss of snowpack, has also reduced postfire tree seedling and shrub establishment, limiting ecosystem recovery.[313,314,315]

Projections suggest that future fire activity will continue to degrade ecosystems and alter their structure and function.[294,298,319] Increased fire activity,[320,321,322] further warming and drying that stress tree seedlings, and model projections of stand-replacing fires at the forest/non-forest boundary in the western US[316] have raised the possibility of shifts in species composition or vegetation type.[294,317] These projections suggest high variability in ecosystem responses depending on interactions between vegetation type, moisture stress, disturbance regimes, and human alterations.[314,319,435,436,437,438]

Increasing wildfire risk poses threats to lives and livelihoods in the region. Wildfire and accompanying smoke have led to fatalities caused by the fires themselves,[304,327] by smoke from wildfires,[328] and by debris flows that occur when heavy rains fall on recently burned slopes.[330] Even if not fatal, wildfires have been linked to declines in physical health[265,328,439] and mental health.[268] Frontline communities, including low-income groups and populations of color, are especially vulnerable to these impacts.[231,338] Exposure of people in the Southwest to wildfire risk is also increasing due to population growth in wildland–urban interface areas near fire-prone forests, shrublands, and grasslands.[331,332,333] Economic costs to individual households come from structures burned and increased insurance and healthcare costs.[440,441] Further costs come from income lost due to fires that affect energy, agriculture, and tourism.[340,341,342,353]

Adaptation strategies include reduction in tree density and wildland fuels[299,355,358,359] that can reduce the size and severity of fires when they occur. Integration of Indigenous burning practices with contemporary forest management can mitigate wildfire risk as well.[296] Risk is expected to be reduced through public safety power shutoffs initiated by electric utilities when weather conditions suggest wildfire danger is especially high.[370]

### Major Uncertainties and Research Gaps

The short-term likelihood of increasing wildfire risks and impacts is very high. What is less clear is the extent to which adaptation strategies such as increasing fuel-reduction treatments and adoption of climate-adapted silviculture will be able to mitigate those impacts. As yet, there has been no reliable way to quantify the degree to which increases in fire area and severity are due to climate change versus past management, non-native species invasions, urbanization, or other factors. To restore forest resilience (KM 7.3), the rate of thinning and fuel reduction needs to be greatly increased, and it is not known whether resources will be available to achieve such intensified management. Fire ecologists point to the need for increasing use of prescribed burning to reduce fuel loads, but it is not certain how much this increase can be achieved, considering the increasing risk of fire escape and public unease about the use of fire as a management tool.[361] Geographic factors, forest policies, and public attitudes toward forest management can constrain the rate at which risk-reduction actions can be implemented. Similarly, long-term attitudes toward public safety power shutoffs, restrictions on homebuilding in fire-prone landscapes, and other risk-reduction policies are uncertain.

## Description of Confidence and Likelihood

There is *high confidence* that the Southwest region is experiencing unprecedented wildfire occurrence and that this change is linked to climate change. Contributing causes include land management policies that have led to high tree densities that increase fuel for fires,[295,318] climate-mediated events such as insect and tree disease outbreaks (Box 7.1),[319] and increased human population at the forest's edge,[331] all of which interact with climate change in ways that increase wildfire risk and occurrence.[18,21]

There is *high confidence* that fires in the region have become larger and more severe. Increased temperatures and changes to precipitation have combined to produce an increase in vapor pressure deficit.[333] This, in conjunction with episodes of climatic extremes such as droughts and heatwaves, means it is *very likely* that these trends will continue in the region's forests.[319,320,321,322] However, there is less certainty about future trends in non-forested areas because of high year-to-year variability in production of the grasses that fuel wildfires,[324] with model projections suggesting that climate impacts on plant growth will vary across the region.[325]

There is *high confidence* that severe wildfires are placing people, economies, ecosystems, and water resources at risk, and it is *very likely* that severe wildfires will continue, partially because of climate change impacts. There is consensus among studies from climate models that the Southwest will continue to warm, and there are multiple indicators that the region is becoming more arid, increasing wildfire risk. There are many indicators of costs to human lives, health, and livelihoods due to wildfire, and as the risk of catastrophic wildfire increases, so do those costs.

There is *medium confidence* that adaptation pathways will reduce wildfire risk and promote ecosystem restoration through forest management and other adaptations such as the application of Indigenous Knowledges. While the adaptation opportunities are known, it is less clear whether society will have the capacity to embrace those opportunities.

# References


1. U.S. Census Bureau. 2010: State Area Measurements and Internal Point Coordinates. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/geographies/reference-files/2010/geo/state-area.html

2. NCEI, 2022: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

3. Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner, 2017: Ch. 6. Temperature changes in the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 185–206. https://doi.org/10.7930/j0n29v45

4. Mote, P.W., S. Li, D.P. Lettenmaier, M. Xiao, and R. Engel, 2018: Dramatic declines in snowpack in the western US. *Npj Climate and Atmospheric Science*, **1** (1), 1–6. https://doi.org/10.1038/s41612-018-0012-1

5. Siirila-Woodburn, E.R., A.M. Rhoades, B.J. Hatchett, L.S. Huning, J. Szinai, C. Tague, P.S. Nico, D.R. Feldman, A.D. Jones, W.D. Collins, and L. Kaatz, 2021: A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment*, **2** (11), 800–819. https://doi.org/10.1038/s43017-021-00219-y

6. Uzun, S., T. Tanir, G.d.A. Coelho, A.d. Souza de Lima, F. Cassalho, and C.M. Ferreira, 2021: Changes in snowmelt runoff timing in the contiguous United States. *Hydrological Processes*, **35** (11), e14430. https://doi.org/10.1002/hyp.14430

7. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

8. Gabbe, C.J. and G. Pierce, 2020: Extreme heat vulnerability of subsidized housing residents in California. *Housing Policy Debate*, **30** (5), 843–860. https://doi.org/10.1080/10511482.2020.1768574

9. Knutson, T.R. and J.J. Ploshay, 2016: Detection of anthropogenic influence on a summertime heat stress index. *Climatic Change*, **138** (1), 25–39. https://doi.org/10.1007/s10584-016-1708-z

10. Li, C., X. Zhang, F. Zwiers, Y. Fang, and A.M. Michalak, 2017: Recent very hot summers in northern hemispheric land areas measured by wet bulb globe temperature will be the norm within 20 years. *Earth's Future*, **5** (12), 1203–1216. https://doi.org/10.1002/2017ef000639

11. Vicedo-Cabrera, A.M., N. Scovronick, F. Sera, D. Royé, R. Schneider, A. Tobias, C. Astrom, Y. Guo, Y. Honda, D.M. Hondula, R. Abrutzky, S. Tong, M.d.S.Z.S. Coelho, P.H.N. Saldiva, E. Lavigne, P.M. Correa, N.V. Ortega, H. Kan, S. Osorio, J. Kyselý, A. Urban, H. Orru, E. Indermitte, J.J.K. Jaakkola, N. Ryti, M. Pascal, A. Schneider, K. Katsouyanni, E. Samoli, F. Mayvaneh, A. Entezari, P. Goodman, A. Zeka, P. Michelozzi, F. de'Donato, M. Hashizume, B. Alahmad, M.H. Diaz, C.D.L.C. Valencia, A. Overcenco, D. Houthuijs, C. Ameling, S. Rao, F. Di Ruscio, G. Carrasco-Escobar, X. Seposo, S. Silva, J. Madureira, I.H. Holobaca, S. Fratianni, F. Acquaotta, H. Kim, W. Lee, C. Iniguez, B. Forsberg, M.S. Ragettli, Y.L.L. Guo, B.Y. Chen, S. Li, B. Armstrong, A. Aleman, A. Zanobetti, J. Schwartz, T.N. Dang, D.V. Dung, N. Gillett, A. Haines, M. Mengel, V. Huber, and A. Gasparrini, 2021: The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, **11** (6), 492–500. https://doi.org/10.1038/s41558-021-01058-x

12. Miller, K., A. Milman, and M. Kiparsky, 2021: Introduction to the Special Collection: Institutional dimensions of groundwater recharge. *Case Studies in the Environment*, **5** (1). https://doi.org/10.1525/cse.2021.1245648

13. Milly, P.C.D. and K.A. Dunne, 2016: Potential evapotranspiration and continental drying. *Nature Climate Change*, **6**, 946–969. https://doi.org/10.1038/nclimate3046

14. Overpeck, J.T. and B. Udall, 2020: Climate change and the aridification of North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (22), 11856–11858. https://doi.org/10.1073/pnas.2006323117

15. Talsma, C.J., K.E. Bennett, and V.V. Vesselinov, 2022: Characterizing drought behavior in the Colorado River Basin using unsupervised machine learning. *Earth and Space Science*, **9** (5), e2021EA002086. https://doi.org/10.1029/2021ea002086

16. Xiao, M., B. Udall, and D.P. Lettenmaier, 2018: On the causes of declining Colorado River streamflows. *Water Resources Research*, **54** (9), 6739–6756. https://doi.org/10.1029/2018wr023153

17. Duane, A., M. Castellnou, and L. Brotons, 2021: Towards a comprehensive look at global drivers of novel extreme wildfire events. *Climatic Change*, **165** (3), 43. https://doi.org/10.1007/s10584-021-03066-4

18. Goss, M., D.L. Swain, J.T. Abatzoglou, A. Sarhadi, C.A. Kolden, A.P. Williams, and N.S. Diffenbaugh, 2020: Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters*, **15** (9), 094016. https://doi.org/10.1088/1748-9326/ab83a7

19. Mueller, S.E., A.E. Thode, E.Q. Margolis, L.L. Yocom, J.D. Young, and J.M. Iniguez, 2020: Climate relationships with increasing wildfire in the southwestern US from 1984 to 2015. *Forest Ecology and Management*, **460**, 117861. https://doi.org/10.1016/j.foreco.2019.117861

20. Swain, D.L., 2021: A shorter, sharper rainy season amplifies California wildfire risk. *Geophysical Research Letters*, **48** (5), e2021GL092843. https://doi.org/10.1029/2021gl092843

21. Williams, A.P., J.T. Abatzoglou, A. Gershunov, J. Guzman-Morales, D.A. Bishop, J.K. Balch, and D.P. Lettenmaier, 2019: Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future*, **7** (8), 892–910. https://doi.org/10.1029/2019ef001210

22. BEA, 2022: Gross Domestic Product by State and Personal Income by State, 2nd Quarter 2022. BEA 22–48. U.S. Department of Commerce, Bureau of Economic Analysis. https://www.bea.gov/data/gdp/gdp-state

23. Bureau of Indian Affairs, 2017: Indian entities recognized and eligible to receive services from the United States Bureau of Indian Affairs. *Federal Register*, **82** (10), 4915–4920. https://www.federalregister.gov/documents/2017/01/17/2017-00912/indian-entities-recognized-and-eligible-to-receive-services-from-the-united-states-bureau-of-indian

24. CRS, 2020: Federal Land Ownership: Overview and Data. CRS Report R42346. Congressional Research Service. https://crsreports.congress.gov/product/pdf/r/r42346

25. Gonzalez, P., G.M. Garfin, D.D. Breshears, K.M. Brooks, H.E. Brown, E.H. Elias, A. Gunasekara, N. Huntly, J.K. Maldonado, N.J. Mantua, H.G. Margolis, S. McAfee, B.R. Middleton, and B.H. Udall, 2018: Ch. 25. Southwest. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1101–1184. https://doi.org/10.7930/nca4.2018.ch25

26. Hoerling, M., J. Eischeid, X. Quan, and A. Badger, 2019: Causes for the century-long decline in Colorado River flow. *Journal of Climate*, **32** (23), 8181–8203. https://doi.org/10.1175/jcli-d-19-0207.1

27. Lukas, J.J. and E.A. Payton, 2020: Colorado River Basin Climate and Hydrology: State of the Science. Western Water Assessment. University of Colorado Boulder, Cooperative Institute for Research in Environmental Sciences, Boulder, CO. https://doi.org/10.25810/3hcv-w477

28. Udall, B. and J. Overpeck, 2017: The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, **53** (3), 2404–2418. https://doi.org/10.1002/2016wr019638

29. Steele, C., J. Reyes, E. Elias, S. Aney, and A. Rango, 2018: Cascading impacts of climate change on southwestern US cropland agriculture. *Climatic Change*, **148** (3), 437–450. https://doi.org/10.1007/s10584-018-2220-4

30. Ebi, K.L., C. Åström, C.J. Boyer, L.J. Harrington, J.J. Hess, Y. Honda, E. Kazura, R.F. Stuart-Smith, and F.E.L. Otto, 2020: Using detection and attribution to quantify how climate change is affecting health. *Health Affairs*, **39** (12), 2168–2174. https://doi.org/10.1377/hlthaff.2020.01004

31. Hait, A.W., 2021: Growth in the Desert Southwest Mirrors the Nation in Some Economic Sectors but Is Quite Different in Others. U.S. Census Bureau. https://www.census.gov/library/stories/2021/09/business-growth-in-desert-southwest-more-than-twice-national-average.html

32. Spencer, N. and M.-A. Urquhart, 2018: Hurricane strikes and migration: Evidence from storms in Central America and the Caribbean. *Weather, Climate, and Society*, **10** (3), 569–577. https://doi.org/10.1175/wcas-d-17-0057.1

33. Newell, J.P., B. Goldstein, and A. Foster, 2019: A 40-year review of food-energy-water nexus literature and its application to the urban scale. *Environmental Research Letters*, **14** (7). https://doi.org/10.1088/1748-9326/ab0767

34. Opejin, A.K., R.M. Aggarwal, D.D. White, J.L. Jones, R. Maciejewski, G. Mascaro, and H.S. Sarjoughian, 2020: A bibliometric analysis of food-energy-water nexus literature. *Sustainability*, **12** (3), 1112. https://doi.org/10.3390/su12031112

35. IPCC, 2022: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844

36. Jones, J.L. and D.D. White, 2022: Understanding barriers to collaborative governance for the food-energy-water nexus: The case of Phoenix, Arizona. *Environmental Science and Policy*, **127**, 111–119. https://doi.org/10.1016/j.envsci.2021.10.025

37. Koebele, E.A., 2020: Cross-coalition coordination in collaborative environmental governance processes. *Policy Studies Journal*, **48** (3), 727–753. https://doi.org/10.1111/psj.12306

38. Sullivan, A., D.D. White, and M. Hanemann, 2019: Designing collaborative governance: Insights from the drought contingency planning process for the lower Colorado River Basin. *Environmental Science and Policy*, **91**, 39–49. https://doi.org/10.1016/j.envsci.2018.10.011

39. The California Climate Crisis Act. Assembly Bill No. 1279, State of California, September 16, 2022. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB1279

40. State of California, 2018: Executive Order B-55-18: To Achieve Carbon Neutrality. State of California, Executive Department. https://www.ca.gov/archive/gov39/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf

41. CARB, 2022: Scoping Plan for Achieving Carbon Neutrality. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/2022-12/2022-sp.pdf

42. State of California, 2021: California Climate Commitment: Biggest Climate Investment in History. State of California, 2 pp. https://www.gov.ca.gov/wp-content/uploads/2022/06/california-climate-commitment-.pdf

43. Climate Action Plan to Reduce Pollution. HB19-1261, State of Colorado, 2019. https://leg.colorado.gov/bills/hb19-1261

44. State of New Mexico, 2019: Executive Order 2019-003: Executive Order on Addressing Climate Change and Energy Waste Prevention. State of New Mexico, Executive Office, 4 pp. https://www.governor.state.nm.us/wp-content/uploads/2019/01/EO_2019-003.pdf

45. Gangopadhyay, S., C.A. Woodhouse, G.J. McCabe, C.C. Routson, and D.M. Meko, 2022: Tree rings reveal unmatched 2nd century drought in the Colorado River Basin. *Geophysical Research Letters*, **49** (11), e2022GL098781. https://doi.org/10.1029/2022gl098781

46. Meko, D.M., C.A. Woodhouse, and A.G. Winitsky, 2022: Tree-ring perspectives on the Colorado River: Looking back and moving forward. JAWRA *Journal of the American Water Resources Association*, **58** (5), 604–621. https://doi.org/10.1111/1752-1688.12989

47. Albano, C.M., J.T. Abatzoglou, D.J. McEvoy, J.L. Huntington, C.G. Morton, M.D. Dettinger, and T.J. Ott, 2022: A Multidataset assessment of climatic drivers and uncertainties of recent trends in evaporative demand across the continental United States. *Journal of Hydrometeorology*, **23** (4), 505–519. https://doi.org/10.1175/jhm-d-21-0163.1

48. Lehner, F., E.R. Wahl, A.W. Wood, D.B. Blatchford, and D. Llewellyn, 2017: Assessing recent declines in Upper Rio Grande runoff efficiency from a paleoclimate perspective. *Geophysical Research Letters*, **44** (9), 4124–4133. https://doi.org/10.1002/2017gl073253

49. Milly, P.C.D. and K.A. Dunne, 2020: Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. *Science*, **367** (6483), 1252–1255. https://doi.org/10.1126/science.aay9187

50. Su, L., Q. Cao, M. Xiao, D.M. Mocko, M. Barlage, D. Li, C.D. Peters-Lidard, and D.P. Lettenmaier, 2021: Drought variability over the conterminous United States for the past century. *Journal of Hydrometeorology*, **22** (5), 1153–1168. https://doi.org/10.1175/jhm-d-20-0158.1

51. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. https://doi.org/10.1038/s41558-022-01290-z

52. Lynn, E., A. Cuthbertson, M. He, J.P. Vasquez, M.L. Anderson, P. Coombe, J.T. Abatzoglou, and B.J. Hatchett, 2020: Technical note: Precipitation-phase partitioning at landscape scales to regional scales. *Hydrology and Earth System Sciences*, **24** (11), 5317–5328. https://doi.org/10.5194/hess-24-5317-2020

53. Skiles, S.M.K., M. Flanner, J.M. Cook, M. Dumont, and T.H. Painter, 2018: Radiative forcing by light-absorbing particles in snow. *Nature Climate Change*, **8** (11), 964–971. https://doi.org/10.1038/s41558-018-0296-5

54. Livneh, B. and A.M. Badger, 2020: Drought less predictable under declining future snowpack. *Nature Climate Change*, **10** (5), 452–458. https://doi.org/10.1038/s41558-020-0754-8

55. Walton, D.B., A. Hall, N. Berg, M. Schwartz, and F. Sun, 2017: Incorporating snow albedo feedback into downscaled temperature and snow cover projections for California's Sierra Nevada. *Journal of Climate*, **30** (4), 1417–1438. https://doi.org/10.1175/jcli-d-16-0168.1

56. Gordon, B.L., P.D. Brooks, S.A. Krogh, G.F.S. Boisrame, R.W.H. Carroll, J.P. McNamara, and A.A. Harpold, 2022: Why does snowmelt-driven streamflow response to warming vary? A data-driven review and predictive framework. *Environmental Research Letters*, **17** (5), 053004. https://doi.org/10.1088/1748-9326/ac64b4

57. Pierce, D.W., 2023: LOCA Statistical Downscaling. University of San Diego, Scripps Institution of Oceanography. https://loca.ucsd.edu/

58. Vano, J., J. Hamman, E. Gutmann, A. Wood, N. Mizukami, M. Clark, D.W. Pierce, D.R. Cayan, C. Wobus, K. Nowak, and J. Arnold, 2020: Comparing Downscaled LOCA and BCSD CMIP5 Climate and Hydrology Projections: Release of Downscaled LOCA CMIP5 Hydrology. Bureau of Reclamation, Livermore, CA, 96 pp. https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/LOCA_BCSD_hydrology_tech_memo.pdf

59. Woodhouse, C.A. and G.T. Pederson, 2018: Investigating runoff efficiency in upper Colorado River streamflow over past centuries. *Water Resources Research*, **54** (1), 286–300. https://doi.org/10.1002/2017wr021663

60. Berg, A. and J. Sheffield, 2018: Climate change and drought: The soil moisture perspective. *Current Climate Change Reports*, **4** (2), 180–191. https://doi.org/10.1007/s40641-018-0095-0

61. Null, S.E. and W.A. Wurtsbaugh, 2020: Ch. 1. Water development, consumptive water uses, and Great Salt Lake. In: *Great Salt Lake Biology: A Terminal Lake in a Time of Change*. Baxter, B.K. and J.K. Butler, Eds. Springer, Cham, Switzerland, 1–21. https://doi.org/10.1007/978-3-030-40352-2_1

62. Mankin, J.S., I. Simpson, A. Hoell, R. Fu, J. Lisonbee, A. Sheffield, and D. Barrie, 2021: NOAA Drought Task Force Report on the 2020–2021 Southwestern U.S. Drought. National Oceanic and Atmospheric Administration Drought Task Force, Modeling, Analysis, Predictions, and Projections Program, and National Integrated Drought Information System. https://www.drought.gov/documents/noaa-drought-task-force-report-2020-2021-southwestern-us-drought

63. Al Atawneh, D., N. Cartwright, and E. Bertone, 2021: Climate change and its impact on the projected values of groundwater recharge: A review. *Journal of Hydrology*, **601**, 126602. https://doi.org/10.1016/j.jhydrol.2021.126602

64. Meixner, T., A.H. Manning, D.A. Stonestrom, D.M. Allen, H. Ajami, K.W. Blasch, A.E. Brookfield, C.L. Castro, J.F. Clark, D.J. Gochis, A.L. Flint, K.L. Neff, R. Niraula, M. Rodell, B.R. Scanlon, K. Singha, and M.A. Walvoord, 2016: Implications of projected climate change for groundwater recharge in the western United States. *Journal of Hydrology*, **534**, 124–138. https://doi.org/10.1016/j.jhydrol.2015.12.027

65. Russo, T.A. and U. Lall, 2017: Depletion and response of deep groundwater to climate-induced pumping variability. *Nature Geoscience*, **10** (2), 105–108. https://doi.org/10.1038/ngeo2883

66. Sheng, Z., 2013: Impacts of groundwater pumping and climate variability on groundwater availability in the Rio Grande Basin. *Ecosphere*, **4** (1), 5. https://doi.org/10.1890/es12-00270.1

67. Lund, J., J. Medellin-Azuara, J. Durand, and K. Stone, 2018: Lessons from California's 2012–2016 drought. *Journal of Water Resources Planning and Management*, **144** (10), 04018067. https://doi.org/10.1061/(asce)wr.1943-5452.0000984

68. Davenport, F.V., J.E. Herrera-Estrada, M. Burke, and N.S. Diffenbaugh, 2020: Flood size increases nonlinearly across the western United States in response to lower snow-precipitation ratios. *Water Resources Research*, **56** (1), e2019WR025571. https://doi.org/10.1029/2019wr025571

69. Li, D., D.P. Lettenmaier, S.A. Margulis, and K. Andreadis, 2019: The role of rain-on-snow in flooding over the conterminous United States. *Water Resources Research*, **55** (11), 8492–8513. https://doi.org/10.1029/2019wr024950

70. Huang, H., M.R. Fischella, Y. Liu, Z. Ban, J.v. Fayne, D. Li, K.C. Cavanaugh, and D.P. Lettenmaier, 2022: Changes in mechanisms and characteristics of western U.S. floods over the last sixty years. *Geophysical Research Letters*, **49** (3). https://doi.org/10.1029/2021gl097022

71. Albano, C.M., M.D. Dettinger, and A.A. Harpold, 2020: Patterns and drivers of atmospheric river precipitation and hydrologic impacts across the western United States. *Journal of Hydrometeorology*, **21** (1), 143–159. https://doi.org/10.1175/jhm-d-19-0119.1

72. Gershunov, A., T. Shulgina, R.E.S. Clemesha, K. Guirguis, D.W. Pierce, M.D. Dettinger, D.A. Lavers, D.R. Cayan, S.D. Polade, J. Kalansky, and F.M. Ralph, 2019: Precipitation regime change in western North America: The role of atmospheric rivers. *Scientific Reports*, **9** (1), 9944. https://doi.org/10.1038/s41598-019-46169-w

73. Pierce, D.W., J.F. Kalansky, and D.R. Cayan, 2018: Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment. California's Fourth Climate Change Assessment. Publication Number: CNRA-CEC-2018-006. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-11/projections_ccca4-cec-2018-006_ada.pdf

74. Wang, J., H. Yin, E. Reyes, T. Smith, and F. Chung, 2018: Mean and Extreme Climate Change Impacts on the State Water Project. California's Fourth Climate Change Assessment. Publication Number: CCCA4-EXT-2018-004. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-12/water_ccca4-ext-2018-004_ada.pdf

75. Hatcher, S.M., C. Agnew-Brune, M. Anderson, L.D. Zambrano, C.E. Rose, M.A. Jim, A. Baugher, G.S. Liu, S.v. Patel, M.E. Evans, T. Pindyck, C.L. Dubray, J.J. Rainey, J. Chen, C. Sadowski, K. Winglee, A. Penman-Aguilar, A. Dixit, E. Claw, and J. McCollum, 2020: COVID-19 among American Indian and Alaska Native persons—23 states, January 31–July 3, 2020. *Morbidity and Mortality Weekly Report*, **69** (34). https://doi.org/10.15585/mmwr.mm6934e1

76. ASCE, 2017: The Economic Benefits of Investing in Water Infrastructure: How a Failure to Act Would Affect the US Economic Recovery. American Society of Civil Engineers. www.downstreamstrategies.com

77. Tanana, H., J. Combs, and A. Hoss, 2021: Water is life: Law, systemic racism, and water security in Indian Country. *Health Security*, **19** (1), 78–82. https://doi.org/10.1089/hs.2021.0034

78. Yang, Y.C.E., K. Son, F. Hung, and V. Tidwell, 2020: Impact of climate change on adaptive management decisions in the face of water scarcity. *Journal of Hydrology*, **588**, 125015. https://doi.org/10.1016/j.jhydrol.2020.125015

79. Sanders, B.F., J.E. Schubert, D.T. Kahl, K.J. Mach, D. Brady, A. AghaKouchak, F. Forman, R.A. Matthew, N. Ulibarri, and S.J. Davis, 2023: Large and inequitable flood risks in Los Angeles, California. *Nature Sustainability*, **6** (1), 47–57. https://doi.org/10.1038/s41893-022-00977-7

80. Schaider, L.A., L. Swetschinski, C. Campbell, and R.A. Rudel, 2019: Environmental justice and drinking water quality: Are there socioeconomic disparities in nitrate levels in U.S. drinking water? *Environmental Health*, **18** (1), 3. https://doi.org/10.1186/s12940-018-0442-6

81. Dobbin, K.B. and M. Lubell, 2021: Collaborative governance and environmental justice: Disadvantaged community representation in California sustainable groundwater management. *Policy Studies Journal*, **49** (2), 562–590. https://doi.org/10.1111/psj.12375

82. Conrad, E., T. Moran, M.E. DuPraw, D. Ceppos, J. Martinez, and W. Blomquist, 2018: Diverse stakeholders create collaborative, multilevel basin governance for groundwater sustainability. *California Agriculture*, **72** (1), 44–53. https://doi.org/10.3733/ca.2018a0002

83. Gilson, G.G. and D.E. Garrick, 2021: Can philanthropy enable collective action to conserve rivers? Insights from a decade of collaboration in the Colorado River Basin. *Conservation and Society*, **19** (3), 190–194. https://doi.org/10.4103/cs.cs_225_20

84. Garcia, M., E. Koebele, A. Deslatte, K. Ernst, K.F. Manago, and G. Treuer, 2019: Towards urban water sustainability: Analyzing management transitions in Miami, Las Vegas, and Los Angeles. *Global Environmental Change*, **58**, 101967. https://doi.org/10.1016/j.gloenvcha.2019.101967

85. Perry, M.D. and S.J. Praskievicz, 2017: A new era of big infrastructure? (Re)developing water storage in the U.S. West in the context of climate change and environmental regulation. *Water Alternatives*, **10** (2), 437–454. https://www.water-alternatives.org/index.php/alldoc/articles/vol10/v10issue2/363-a10-2-13/file

86. Quay, R., F. Sternlieb, E. Rauh, R. Andrade, A. Bartholomew, D. White, J. Holway, Z. Sugg, and E. Rugland, 2022: Evaluating the effectiveness of land and water integrative practices for achieving water sustainability within the Colorado River Basin: Perceptions and indicators. *Water International*, **47** (2), 257–277. https://doi.org/10.1080/02508060.2022.2041281

87. Sterle, K. and L. Singletary, 2017: Adapting to variable water supply in the Truckee-Carson River system, western USA. *Water*, **9** (10), 768. https://doi.org/10.3390/w9100768

88. White, D.D., E.K. Rauh, A. Sullivan, K.L. Larson, A. Wutich, D. Linthicum, V. Horvath, and K.L. Lawless, 2019: Public attitudes toward urban water sustainability transitions: A multi-city survey in the western United States. *Sustainability Science*, **14** (6), 1469–1483. https://doi.org/10.1007/s11625-019-00658-z

89. Obringer, R. and D.D. White, 2023: Leveraging unsupervised learning to develop a typology of residential water users' attitudes towards conservation. *Water Resources Management*, **37** (1), 37–53. https://doi.org/10.1007/s11269-022-03354-3

90. USBR, 2021: Reclamation Announces 2022 Operating Conditions for Lake Powell and Lake Mead. U.S. Bureau of Reclamation. https://www.usbr.gov/newsroom/news-release/3950

91. Black & Veatch, 2020: Binational Study of Water Desalination Opportunities in the Sea of Cortez. TM1: Water Supply Availability and Demand Analysis. Prepared for Minute 323 Desalination Work Group. B&V Project No. 400584. Black & Veatch. https://www.ibwc.gov/wp-content/uploads/2023/04/TMs_All_Portfolio.pdf

92. OCM, 2023: California. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management, accessed July 19, 2023. https://coast.noaa.gov/states/california.html

93. OCM, 2015: The National Significance of California's Ocean Economy. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. https://coast.noaa.gov/digitalcoast/training/california-ocean-economy.html

94. CalEPA, 2018: Coastal Ocean Temperature: Ocean Waters Along California's Coast Are Warming. California Environmental Protection Agency, Office of Environmental Health Hazard Assessment, 2 pp. https://oehha.ca.gov/media/epic/downloads/15coastoceantemp_19dec2018.pdf

95. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

96. Pozo Buil, M., M.G. Jacox, J. Fiechter, M.A. Alexander, S.J. Bograd, E.N. Curchitser, C.A. Edwards, R.R. Rykaczewski, and C.A. Stock, 2021: A dynamically downscaled ensemble of future projections for the California Current System. *Frontiers in Marine Science*, **8**, 612874. https://doi.org/10.3389/fmars.2021.612874

97. Di Lorenzo, E. and N. Mantua, 2016: Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, **6**, 1042–1047. https://doi.org/10.1038/nclimate3082

98. Fumo, J.T., M.L. Carter, R.E. Flick, L.L. Rasmussen, D.L. Rudnick, and S.F. Iacobellis, 2020: Contextualizing marine heatwaves in the Southern California Bight under anthropogenic climate change. *Journal of Geophysical Research: Oceans*, **125** (5), e2019JC015674. https://doi.org/10.1029/2019jc015674

99. Oliver, E.C.J., M.G. Donat, M.T. Burrows, P.J. Moore, D.A. Smale, L.V. Alexander, J.A. Benthuysen, M. Feng, A. Sen Gupta, A.J. Hobday, N.J. Holbrook, S.E. Perkins-Kirkpatrick, H.A. Scannell, S.C. Straub, and T. Wernberg, 2018: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, **9** (1), 1324. https://doi.org/10.1038/s41467-018-03732-9

100. Shi, H., M. García-Reyes, M.G. Jacox, R.R. Rykaczewski, B.A. Black, S.J. Bograd, and W.J. Sydeman, 2021: Co-occurrence of California drought and northeast Pacific marine heatwaves under climate change. *Geophysical Research Letters*, **48** (17), e2021GL092765. https://doi.org/10.1029/2021gl092765

101. Nielsen, J.M., L.A. Rogers, R.D. Brodeur, A.R. Thompson, T.D. Auth, A.L. Deary, J.T. Duffy-Anderson, M. Galbraith, J.A. Koslow, and R.I. Perry, 2021: Responses of ichthyoplankton assemblages to the recent marine heatwave and previous climate fluctuations in several Northeast Pacific marine ecosystems. *Global Change Biology*, **27** (3), 506–520. https://doi.org/10.1111/gcb.15415

102. Koenigstein, S., M.G. Jacox, M. Pozo Buil, J. Fiechter, B.A. Muhling, S. Brodie, P.T. Kuriyama, T.D. Auth, E.L. Hazen, S.J. Bograd, and D. Tommasi, 2022: Population projections of Pacific sardine driven by ocean warming and changing food availability in the California Current. *ICES Journal of Marine Science*, **79** (9), 2510–2523. https://doi.org/10.1093/icesjms/fsac191

103. von Biela, V.R., M.L. Arimitsu, J.F. Piatt, B. Heflin, S.K.T.J.L. Schoen, and C.M. Clawson, 2019: Extreme reduction in nutritional value of a key forage fish during the Pacific marine heatwave of 2014–2016. *Marine Ecology Progress Series*, **613**, 171–182. https://doi.org/10.3354/meps12891

104. Jones, T., J.K. Parrish, W.T. Peterson, E.P. Bjorkstedt, N.A. Bond, L.T. Ballance, V. Bowes, J.M. Hipfner, H.K. Burgess, J.E. Dolliver, K. Lindquist, J. Lindsey, H.M. Nevins, R.R. Robertson, J. Roletto, L. Wilson, T. Joyce, and J. Harvey, 2018: Massive mortality of a planktivorous seabird in response to a marine heatwave. *Geophysical Research Letters*, **45** (7), 3193–3202. https://doi.org/10.1002/2017gl076164

105. Piatt, J.F., J.K. Parrish, H.M. Renner, S.K. Schoen, T.T. Jones, M.L. Arimitsu, K.J. Kuletz, B. Bodenstein, M. García-Reyes, R.S. Duerr, R.M. Corcoran, R.S.A. Kaler, G.J. McChesney, R.T. Golightly, H.A. Coletti, R.M. Suryan, H.K. Burgess, J. Lindsey, K. Lindquist, P.M. Warzybok, J. Jahncke, J. Roletto, and W.J. Sydeman, 2020: Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014–2016. *PLoS ONE*, **15** (1), e0226087. https://doi.org/10.1371/journal.pone.0226087

106. Tolowa Dee-ni' Nation, InterTribal Sinkyone Wilderness Council, Cher-Ae Heights Indian Community of the Trinidad Rancheria, and Wiyot Tribe, 2017: Informing the North Coast MPA Baseline: Traditional Ecological Knowledge of Keystone Marine Species and Ecosystems. University of California, San Diego. https://caseagrant.ucsd.edu/sites/default/files/39-Rocha-Final.pdf

107. Cheung, W.W.L. and T.L. Frölicher, 2020: Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. *Scientific Reports*, **10** (1), 6678. https://doi.org/10.1038/s41598-020-63650-z

108. Fisher, M.C., S.K. Moore, S.L. Jardine, J.R. Watson, and J.F. Samhouri, 2021: Climate shock effects and mediation in fisheries. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2014379117. https://doi.org/10.1073/pnas.2014379117

109. Smith, J.A., M. Pozo Buil, B. Muhling, D. Tommasi, S. Brodie, T.H. Frawley, J. Fiechter, S. Koenigstein, A. Himes-Cornell, M.A. Alexander, S.J. Bograd, N. Cordero Quirós, L.B. Crowder, E. Curchitser, S.J. Green, N.A. Hardy, A.C. Haynie, E.L. Hazen, K. Holsman, G. Le Fol, N. Lezama-Ochoa, R.R. Rykaczewski, C.A. Stock, S. Stohs, J. Sweeney, H. Welch, and M.G. Jacox, 2023: Projecting climate change impacts from physics to fisheries: A view from three California Current fisheries. *Progress in Oceanography*, **211**, 102973. https://doi.org/10.1016/j.pocean.2023.102973

110. CalEPA, 2022: Indicators of Climate Change in California: Impacts on Tribes. California Environmental Protection Agency, Office of Environmental Health Hazard Assessment. https://oehha.ca.gov/media/tribalsection2022.pdf

111. Wei, X., K.-Y. Li, T. Kilpatrick, M. Wang, and S.-P. Xie, 2021: Large-scale conditions for the record-setting Southern California marine heatwave of August 2018. *Geophysical Research Letters*, **48** (7), e2020GL091803. https://doi.org/10.1029/2020gl091803

112. Chen, Z., J. Shi, Q. Liu, H. Chen, and C. Li, 2021: A persistent and intense marine heatwave in the Northeast Pacific during 2019–2020. *Geophysical Research Letters*, **48** (13), e2021GL093239. https://doi.org/10.1029/2021gl093239

113. McCabe, R.M., B.M. Hickey, R.M. Kudela, K.A. Lefebvre, N.G. Adams, B.D. Bill, F.M.D. Gulland, R.E. Thomson, W.P. Cochlan, and V.L. Trainer, 2016: An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, **43** (19), 10366–10376. https://doi.org/10.1002/2016gl070023

114. Holland, D.S. and J. Leonard, 2020: Is a delay a disaster? Economic impacts of the delay of the california Dungeness crab fishery due to a harmful algal bloom. *Harmful Algae*, **98**, 101904. https://doi.org/10.1016/j.hal.2020.101904

115. Samhouri, J.F., B.E. Feist, M.C. Fisher, O. Liu, S.M. Woodman, B. Abrahms, K.A. Forney, E.L. Hazen, D. Lawson, J. Redfern, and L.E. Saez, 2021: Marine heatwave challenges solutions to human-wildlife conflict. *Proceedings of the Royal Society B: Biological Sciences*, **288** (1964), 20211607. https://doi.org/10.1098/rspb.2021.1607

116. Santora, J.A., N.J. Mantua, I.D. Schroeder, J.C. Field, E.L. Hazen, S.J. Bograd, W.J. Sydeman, B.K. Wells, J. Calambokidis, L. Saez, D. Lawson, and K.A. Forney, 2020: Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications*, **11** (1), 536. https://doi.org/10.1038/s41467-019-14215-w

117. Rogers-Bennett, L. and C.A. Catton, 2019: Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports*, **9** (1), 15050. https://doi.org/10.1038/s41598-019-51114-y

118. Rogers-Bennett, L., R. Klamt, and C.A. Catton, 2021: Survivors of climate driven abalone mass mortality exhibit declines in health and reproduction following kelp forest collapse. *Frontiers in Marine Science*, **8**, 725134. https://doi.org/10.3389/fmars.2021.725134

119. Jardine, S.L., M.C. Fisher, S.K. Moore, and J.F. Samhouri, 2020: Inequality in the economic impacts from climate shocks in fisheries: The case of harmful algal blooms. *Ecological Economics*, **176**, 106691. https://doi.org/10.1016/j.ecolecon.2020.106691

120. Freedman, R.M., J.A. Brown, C. Caldow, and J.E. Caselle, 2020: Marine protected areas do not prevent marine heatwave-induced fish community structure changes in a temperate transition zone. *Scientific Reports*, **10** (1), 21081. https://doi.org/10.1038/s41598-020-77885-3

121. Kawana, S.K., C.A. Catton, J.K.K. Hofmeister, C.I. Juhasz, I.K. Taniguchi, D.M. Stein, and L. Rogers-Bennett, 2019: Warm water shifts abalone recruitment and sea urchin diversity in Southern California: Implications for climate-ready abalone restoration planning. *Journal of Shellfish Research*, **38** (2), 475–484. https://doi.org/10.2983/035.038.0231

122. Munsch, S.H., C.M. Greene, N.J. Mantua, and W.H. Satterthwaite, 2022: One hundred-seventy years of stressors erode salmon fishery climate resilience in California's warming landscape. *Global Change Biology*, **28** (7), 2183–2201. https://doi.org/10.1111/gcb.16029

123. Holsman, K.K., A.C. Haynie, A.B. Hollowed, J.C.P. Reum, K. Aydin, A.J. Hermann, W. Cheng, A. Faig, J.N. Ianelli, K.A. Kearney, and A.E. Punt, 2020: Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications*, **11** (1), 4579. https://doi.org/10.1038/s41467-020-18300-3

124. Ekstrom, J.A., S.K. Moore, and T. Klinger, 2020: Examining harmful algal blooms through a disaster risk management lens: A case study of the 2015 U.S. West Coast domoic acid event. *Harmful Algae*, **94**, 101740. https://doi.org/10.1016/j.hal.2020.101740

125. Hartog, J.R., C.M. Spillman, G. Smith, and A.J. Hobday, 2023: Forecasts of marine heatwaves for marine industries: Reducing risk, building resilience and enhancing management responses. *Deep Sea Research Part II: Topical Studies in Oceanography*, **209**, 105276. https://doi.org/10.1016/j.dsr2.2023.105276

126. Fiechter, J., M. Pozo Buil, M.G. Jacox, M.A. Alexander, and K.A. Rose, 2021: Projected shifts in 21st century sardine distribution and catch in the California Current. *Frontiers in Marine Science*, **8**, 685241. https://doi.org/10.3389/fmars.2021.685241

127. Clements, J.C. and T. Chopin, 2017: Ocean acidification and marine aquaculture in North America: Potential impacts and mitigation strategies. *Reviews in Aquaculture*, **9** (4), 326–341. https://doi.org/10.1111/raq.12140

128. Klinger, T., E.A. Chornesky, E.A. Whiteman, F. Chan, J.L. Largier, and W.W. Wakefield, 2017: Using integrated, ecosystem-level management to address intensifying ocean acidification and hypoxia in the California Current large marine ecosystem. *Elementa: Science of the Anthropocene*, **5**, 16. https://doi.org/10.1525/elementa.198

129. Beheshti, K.M., S.L. Williams, K.E. Boyer, C. Endris, A. Clemons, T. Grimes, K. Wasson, and B.B. Hughes, 2022: Rapid enhancement of multiple ecosystem services following the restoration of a coastal foundation species. *Ecological Applications*, **32** (1), e02466. https://doi.org/10.1002/eap.2466

130. Hirsh, H.K., K.J. Nickols, Y. Takeshita, S.B. Traiger, D.A. Mucciarone, S. Monismith, and R.B. Dunbar, 2020: Drivers of biogeochemical variability in a central California kelp forest: Implications for local amelioration of ocean acidification. *Journal of Geophysical Research: Oceans*, **125** (11), e2020JC016320. https://doi.org/10.1029/2020jc016320

131. Chavez, F.P., C. Costello, D. Aseltine-Neilson, H. Doremus, J.C. Field, S.D. Gaines, M. Hall-Arber, N.J. Mantua, B. McCovey, C. Pomeroy, L. Sievanen, W. Sydeman, and S.A. Wheeler, 2017: Readying California Fisheries for Climate Change. California Ocean Science Trust, Oakland, CA. https://www.oceansciencetrust.org/wp-content/uploads/2016/06/Climate-and-Fisheries_GuidanceDoc.pdf

132. Alleway, H.K., C.L. Gillies, M.J. Bishop, R.R. Gentry, S.J. Theuerkauf, and R. Jones, 2019: The ecosystem services of marine aquaculture: Valuing benefits to people and nature. *BioScience*, **69** (1), 59–68. https://doi.org/10.1093/biosci/biy137

133. Froehlich, H.E., J.C. Afflerbach, M. Frazier, and B.S. Halpern, 2019: Blue growth potential to mitigate climate change through seaweed offsetting. *Current Biology*, **29** (18), 3087–3093. https://doi.org/10.1016/j.cub.2019.07.041

134. Froehlich, H.E., R.R. Gentry, and B.S. Halpern, 2017: Conservation aquaculture: Shifting the narrative and paradigm of aquaculture's role in resource management. *Biological Conservation*, **215**, 162–168. https://doi.org/10.1016/j.biocon.2017.09.012

135. Theuerkauf, S.J., B.J. Puckett, and D.B. Eggleston, 2021: Metapopulation dynamics of oysters: Sources, sinks, and implications for conservation and restoration. *Ecosphere*, **12** (7), e03573. https://doi.org/10.1002/ecs2.3573

136. Kübler, J.E., S.R. Dudgeon, and D. Bush, 2021: Climate change challenges and opportunities for seaweed aquaculture in California, the United States. *Journal of the World Aquaculture Society*, **52** (5), 1069–1080. https://doi.org/10.1111/jwas.12794

137. Titus, J.G., 2023: Population in floodplains or close to sea level increased in US but declined in some counties—Especially among black residents. *Environmental Research Letters*, **18** (3), 034001. https://doi.org/10.1088/1748-9326/acadf5

138. Befus, K.M., P.L. Barnard, D.J. Hoover, J.A. Finzi Hart, and C.I. Voss, 2020: Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nature Climate Change*, **10** (10), 946–952. https://doi.org/10.1038/s41558-020-0874-1

139. Bruzgul, J., R. Kay, A. Petrow, T. Hendrickson, B. Rodehorst, D. Revell, M. Bruguera, D. Moreno, and K. Collison, 2018: Rising Seas and Electricity Infrastructure: Potential Impacts and Adaptation Actions for San Diego Gas & Electric. California's Fourth Climate Change Assessment. Publication Number: CCCA4-CEC-2018-004. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-11/energy_ccca4-cec-2018-004_ada.pdf

140. Buchanan, M.K., S. Kulp, L. Cushing, R. Morello-Frosch, T. Nedwick, and B. Strauss, 2020: Sea level rise and coastal flooding threaten affordable housing. *Environmental Research Letters*, **15** (12), 124020. https://doi.org/10.1088/1748-9326/abb266

141. Hoover, D.J., K.O. Odigie, P.W. Swarzenski, and P. Barnard, 2017: Sea-level rise and coastal groundwater inundation and shoaling at select sites in California, USA. *Journal of Hydrology: Regional Studies*, **11**, 234–249. https://doi.org/10.1016/j.ejrh.2015.12.055

142. Nicholls, R.J., D. Lincke, J. Hinkel, S. Brown, A.T. Vafeidis, B. Meyssignac, S.E. Hanson, J.-L. Merkens, and J. Fang, 2021: A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nature Climate Change*, **11** (4), 338–342. https://doi.org/10.1038/s41558-021-00993-z

143. Radke, J.D., G.S. Biging, K. Roberts, M. Schmidt-Poolman, H. Foster, E. Roe, Y. Ju, S. Lindbergh, T. Beach, L. Maier, Y. He, M. Ashenfarb, P. Norton, M. Wray, A. Alruheili, S. Yi, R. Rau, J. Collins, D. Radke, M. Coufal, S. Marx, A. Gohar, D. Moanga, V. Ulyashin, and A. Dalal, 2018: Assessing Extreme Weather-Related Vulnerability and Identifying Resilience Options for California's Interdependent Transportation Fuel Sector. California's Fourth Climate Change Assessment. Publication Number: CCCA4-CEC-2018-012. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-11/energy_ccca4-cec-2018-012_ada.pdf

144. Caltrans, 2022: Sea Level Rise and the Transportation System in the Coastal Zone. California Department of Transportation. https://dot.ca.gov/programs/environmental-analysis/coastal-program/coastal-act-policy-resource-information/coastal-hazards/sea-level-rise

145. Martinich, J., J. Neumann, L. Ludwig, and L. Jantarasami, 2013: Risks of sea level rise to disadvantaged communities in the United States. *Mitigation and Adaptation Strategies for Global Change*, **18** (2), 169–185. https://doi.org/10.1007/s11027-011-9356-0

146. Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi, 2014: Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, **2** (8), 383–406. https://doi.org/10.1002/2014ef000239

147. Tebaldi, C., B.H. Strauss, and C.E. Zervas, 2012: Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters*, **7** (1), 014032. https://doi.org/10.1088/1748-9326/7/1/014032

148. Morello-Frosch, R., 2020: Toxic Tides: Sea Level Rise, Hazardous Sites, and Environmental Justice in California. University of California, Berkeley. https://sites.google.com/berkeley.edu/toxictides/home

149. OEHHA, 2021: CalEnviroScreen 4.0. California Office of Environmental Health Hazard Assessment. https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40

150. Keenan, J.M., T. Hill, and A. Gumber, 2018: Climate gentrification: From theory to empiricism in Miami-Dade County, Florida. *Environmental Research Letters*, **13** (5), 054001. https://doi.org/10.1088/1748-9326/aabb32

151. Blackwell, E., M. Shirzaei, C. Ojha, and S. Werth, 2020: Tracking California's sinking coast from space: Implications for relative sea-level rise. *Science Advances*, **6** (31), 4551. https://doi.org/10.1126/sciadv.aba4551

152. Fu, X., 2020: Measuring local sea-level rise adaptation and adaptive capacity: A national survey in the United States. *Cities*, **102**, 102717. https://doi.org/10.1016/j.cities.2020.102717

153. Moser, S.C., J.A. Finzi Hart, A.G. Newton Mann, N. Sadrpour, and P.M. Grifman, 2018: Growing Effort, Growing Challenge: Findings from the 2016 CA Coastal Adaptation Needs Assessment Survey. California's Fourth Climate Change Assessment. CCCA4-EXT-2018-009. California Natural Resources Agency. https://www.energy.ca.gov/sites/default/files/2019-12/Oceans_CCCA4-EXT-2018-009_ada.pdf

154. An Act to Amend Section 65302 of the Government Code, Relating to Land Use. Senate Bill No. 379, Chapter 608, State of California, October 8, 2015. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB379

155. CAL OES, 2020: California Adaptation Planning Guide. California Governor's Office of Emergency Services, Mather, CA. https://www.caloes.ca.gov/ca-adaptation-planning-guide-final-june-2020-accessible/

156. State of California, 2015: Executive Order B-30-15: Governor Brown Establishes Most Ambitious Greenhouse Gas Reduction Target in North America. State of California, Office of the Governor, Sacramento, CA. https://www.ca.gov/archive/gov39/2015/04/29/news18938/index.html

157. State of California, 2019: Executive Order N-19-19: To Require the Redoubling of the State's "Efforts to Reduce Greenhouse Gas Emissions and Mitigate the Impacts of Climate Change While Building a Sustainable, Inclusive Economy". State of California, Office of the Governor. https://www.adaptationclearinghouse.org/resources/state-of-california-executive-order-n-19-19.html

158. California Coastal Commission, 2021: Critical Infrastructure at Risk: Sea Level Rise Planning Guidance for California's Coastal Zone. California Coastal Commission, San Francisco, CA. https://www.coastal.ca.gov/climate/slr/vulnerability-adaptation/infrastructure/

159. California Ocean Protection Council, 2018: State of California Sea-Level Rise Guidance 2018 Update. State of California, 84 pp. https://www.adaptationclearinghouse.org/resources/california-sea-level-rise-guidance-2018-update.html

160. Governor's Office of Planning and Research, 2022: The ResilientCA Adaptation Planning Map (RAP-Map). State of California, Governor's Office of Planning and Research. https://resilientca.org/rap-map/

161. Moser, S.C., J.A. Ekstrom, J. Kim, and S. Heitsch, 2018: Adaptation Finance Challenges: Characteristic Patterns Facing California Local Governments and Ways to Overcome Them. California's Fourth Climate Change Assessment. Publication Number: CCCA4-CNRA2018-007. California Natural Resources Agency. https://www.energy.ca.gov/sites/default/files/2019-12/governance_ccca4-cnra-2018-007_ada.pdf

162. Matthews, S.N., L.R. Iverson, M.P. Peters, and A.M. Prasad, 2018: Assessing Potential Climate Change Pressures Across the Conterminous United States: Mapping Plant Hardiness Zones, Heat Zones, Growing Degree Days, and Cumulative Drought Severity Throughout This Century. RMAP-NRS-9. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, 31 pp. https://doi.org/10.2737/nrs-rmap-9

163. Marklein, A., E. Elias, P. Nico, and K. Steenwerth, 2020: Projected temperature increases may require shifts in the growing season of cool-season crops and the growing locations of warm-season crops. *Science of The Total Environment*, **746**, 140918. https://doi.org/10.1016/j.scitotenv.2020.140918

164. Jin, Y., B. Chen, B.D. Lampinen, and P.H. Brown, 2020: Advancing agricultural production with machine learning analytics: Yield determinants for California's almond orchards. *Frontiers in Plant Science*, **11**, 290. https://doi.org/10.3389/fpls.2020.00290

165. Parker, L.E., N. Zhang, J.T. Abatzoglou, S.M. Ostoja, and T.B. Pathak, 2022: Observed changes in agroclimate metrics relevant for specialty crop production in California. *Agronomy*, **12** (1), 205. https://doi.org/10.3390/agronomy12010205

166. Kral-O'Brien, K.C., P.L. O'Brien, and J.P. Harmon, 2019: Need for false spring research in the northern Great Plains, USA. *Agricultural & Environmental Letters*, **4** (1), 190025. https://doi.org/10.2134/ael2019.07.0025

167. Guirguis, K., A. Gershunov, D.R. Cayan, and D.W. Pierce, 2018: Heat wave probability in the changing climate of the Southwest US. *Climate Dynamics*, **50** (9–10), 3853–3864. https://doi.org/10.1007/s00382-017-3850-3

168. Ayankojo, I.T., K.R. Thorp, K. Morgan, K. Kothari, and S. Ale, 2020: Assessing the impacts of future climate on cotton production in the Arizona low desert. *Transactions of the* ASABE, **63** (4), 1087–1098. https://doi.org/10.13031/trans.13731

169. Pathak, T.B., M.L. Maskey, J.A. Dahlberg, F. Kearns, K.M. Bali, and D. Zaccaria, 2018: Climate change trends and impacts on California agriculture: A detailed review. *Agronomy*, **8** (3), 25. https://doi.org/10.3390/agronomy8030025

170. Conrad, L.M., A.G. Fernald, S.J. Guldan, and C.G. Ochoa, 2022: A water balancing act: Water balances highlight the benefits of community-based adaptive management in northern New Mexico, USA. *Hydrology*, **9** (4), 64. https://doi.org/10.3390/hydrology9040064

171. Duniway, M.C., A.A. Pfennigwerth, S.E. Fick, T.W. Nauman, J. Belnap, and N.N. Barger, 2019: Wind erosion and dust from US drylands: A review of causes, consequences, and solutions in a changing world. *Ecosphere*, **10** (3), e02650. https://doi.org/10.1002/ecs2.2650

172. Finger-Higgens, R., M.C. Duniway, S. Fick, E.L. Geiger, D.L. Hoover, A.A. Pfennigwerth, M.W. Van Scoyoc, and J. Belnap, 2022: Decline in biological soil crust N-fixing lichens linked to increasing summertime temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (16), e2120975119. https://doi.org/10.1073/pnas.2120975119

173. Fassnacht, S.R., C.R. Duncan, A.K.D. Pfohl, R.W. Webb, J.E. Derry, W.E. Sanford, D.C. Reimanis, and L.G. Doskocil, 2022: Drivers of dust-enhanced snowpack melt-out and streamflow timing. *Hydrology*, **9** (3), 47. https://doi.org/10.3390/hydrology9030047

174. ERS, 2020: Ag and Food Statistics: Charting the Essentials. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/

175. CDFA, 2022: California Agricultural Production Statistics. California Department of Food and Agriculture. https://www.cdfa.ca.gov/statistics/

176. NASS, 2022: Data and Statistics, October 2022. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/data_and_statistics/index.php

177. Parajuli, R., G. Thoma, and M.D. Matlock, 2019: Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: A review. *Science of The Total Environment*, **650**, 2863–2879. https://doi.org/10.1016/j.scitotenv.2018.10.019

178. Davis, K.F., S. Downs, and J.A. Gephart, 2021: Towards food supply chain resilience to environmental shocks. *Nature Food*, **2** (1), 54–65. https://doi.org/10.1038/s43016-020-00196-3

179. Medellín-Azuara, J., A. Escriva-Bou, J.A. Abatzoglou, J.H. Viers, S.A. Cole, J.M. Rodríguez-Flores, and D.A. Sumner, 2022: Economic Impacts of the 2021 Drought on California Agriculture: Preliminary Report. University of California, Merced. https://wsm.ucmerced.edu/wp-content/uploads/2022/02/2021-Drought-Impact-Assessment_20210224.pdf

180. Monteverde, C. and F. De Sales, 2020: Impacts of global warming on southern California's winegrape climate suitability. *Advances in Climate Change Research*, **11** (3), 279–293. https://doi.org/10.1016/j.accre.2020.08.002

181. Parker, L.E., A.J. McElrone, S.M. Ostoja, and E.J. Forrestel, 2020: Extreme heat effects on perennial crops and strategies for sustaining future production. *Plant Science*, **295**, 110397. https://doi.org/10.1016/j.plantsci.2019.110397

182. Hanak, E., A. Escriva-Bou, B. Gray, S. Green, T. Harter, J. Jezdimirovic, J. Lund, J. Medellín-Azuara, P. Moyle, and N. Seavy, 2019: Water and the Future of the San Joaquin Valley. Public Policy Institute of California, 100 pp. https://www.ppic.org/publication/water-and-the-future-of-the-san-joaquin-valley/

183. Morris, J.L., S. Cottrell, C.J. Fettig, R.J. DeRose, K.M. Mattor, V.A. Carter, J. Clear, J. Clement, W.D. Hansen, J.A. Hicke, P.E. Higuera, A.W. Seddon, H. Seppä, R.L. Sherriff, J.D. Stednick, and S.J. Seybold, 2018: Bark beetles as agents of change in social–ecological systems. *Frontiers in Ecology and the Environment*, **16** (S1), S34–S43. https://doi.org/10.1002/fee.1754

184. Standiford, R., S.L. Evans, and J. Henderson, 2020: Economic Contribution of California's Forestry and Forest-Products Sectors. Publication Number: 8670. University of California, Agriculture and Natural Resources, 17 pp. https://anrcatalog.ucanr.edu/details.aspx?itemno=8670

185. Ortiz-Bobea, A., E. Knippenberg, and R.G. Chambers, 2018: Growing climatic sensitivity of U.S. agriculture linked to technological change and regional specialization. *Science Advances*, **4** (12), 4343. https://doi.org/10.1126/sciadv.aat4343

186. Bae, J. and S. Dall'erba, 2018: Crop production, export of virtual water and water-saving strategies in Arizona. *Ecological Economics*, **146**, 148–156. https://doi.org/10.1016/j.ecolecon.2017.10.018

187. York, A.M., H. Eakin, J.C. Bausch, S. Smith-Heisters, J.M. Anderies, R. Aggarwal, B. Leonard, and K. Wright, 2020: Agricultural water governance in the desert: Shifting risks in central Arizona. *Water Alternatives*, **13** (2), 418–445. https://www.water-alternatives.org/index.php/alldoc/articles/vol13/v13issue2/582-a13-2-11/file

188. Abbott, B.W., B.K. Baxter, K. Busche, L.d. Freitas, R. Frei, T. Gomez, M.A. Karren, R.L. Buck, J. Price, S. Frutos, R.B. Sowby, J. Brahney, B.G. Hopkins, M.F. Bekker, J.S. Bekker, R. Rader, B. Brown, M. Proteau, G.T. Carling, L. Conner, P.A. Cox, E. McQuhae, C. Oscarson, D.T. Nelson, R.J. Davis, D. Horns, H. Dove, T. Bishop, A. Johnson, K. Nelson, J. Bennion, and P. Belmont, 2023: Emergency Measures Needed to Rescue Great Salt Lake from Ongoing Collapse. Brigham Young University, College of Life Sciences, Plant and Wildlife Sciences, 34 pp. https://pws.byu.edu/great-salt-lake

189. Reyes, J.J. and E. Elias, 2019: Spatio-temporal variation of crop loss in the United States from 2001 to 2016. *Environmental Research Letters*, **14** (7), 074017. https://doi.org/10.1088/1748-9326/ab1ac9

190. Johnson, K.M. and D.T. Lichter, 2019: Rural depopulation: Growth and decline processes over the past century. *Rural Sociology*, **84** (1), 3–27. https://doi.org/10.1111/ruso.12266

191. Lichter, D.T., D.L. Brown, and D. Parisi, 2021: The rural–urban interface: Rural and small town growth at the metropolitan fringe. *Population, Space and Place*, **27** (3), e2415. https://doi.org/10.1002/psp.2415

192. Ahmed, S. and D. Jackson-Smith, 2019: Impacts of spatial patterns of rural and exurban residential development on agricultural trends in the Intermountain West. *SAGE Open*, **9** (3). https://doi.org/10.1177/2158244019871037

193. Park, S. and S. Deller, 2021: Effect of farm structure on rural community well-being. *Journal of Rural Studies*, **87**, 300–313. https://doi.org/10.1016/j.jrurstud.2021.09.014

194. Stahle, D.W., 2020: Anthropogenic megadrought. *Science*, **368** (6488), 238–239. https://doi.org/10.1126/science.abb6902

195. Havstad, K.M., J.R. Brown, R. Estell, E. Elias, A. Rango, and C. Steele, 2018: Vulnerabilities of southwestern U.S. rangeland-based animal agriculture to climate change. *Climatic Change*, **148** (3), 371–386. https://doi.org/10.1007/s10584-016-1834-7

196. Holechek, J.L., H.M.E. Geli, A.F. Cibils, and M.N. Sawalhah, 2020: Climate change, rangelands, and sustainability of ranching in the western United States. *Sustainability*, **12** (12), 4942. https://doi.org/10.3390/su12124942

197. Brice, E.M., B.A. Miller, H. Zhang, K. Goldstein, S.N. Zimmer, G.J. Grosklos, P. Belmont, C.G. Flint, J.E. Givens, P.B. Adler, M.W. Brunson, and J.W. Smith, 2020: Impacts of climate change on multiple use management of Bureau of Land Management land in the Intermountain West, USA. *Ecosphere*, **11** (11), e03286. https://doi.org/10.1002/ecs2.3286

198. Godde, C.M., D. Mason-D'Croz, D.E. Mayberry, P.K. Thornton, and M. Herrero, 2021: Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, **28**, 100488. https://doi.org/10.1016/j.gfs.2020.100488

199. Dinan, M., P.B. Adler, J. Bradford, M. Brunson, E. Elias, A. Felton, C. Greene, J. James, K. Suding, and E. Thacker, 2021: Making research relevant: Sharing climate change research with rangeland advisors to transform results into drought resilience. *Rangelands*, **43** (5), 185–193. https://doi.org/10.1016/j.rala.2021.08.004

200. Flörke, M., C. Schneider, and R.I. McDonald, 2018: Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, **1** (1), 51–58. https://doi.org/10.1038/s41893-017-0006-8

201. Bray, L.A., 2022: Water justice across the rural-urban interface: The making of hydrosocial territories in New Mexico's Rio Grande Valley. *Society & Natural Resources*, **35** (3), 320–337. https://doi.org/10.1080/08941920.2022.2032893

202. Dilling, L., J. Berggren, J. Henderson, and D. Kenney, 2019: Savior of rural landscapes or Solomon's choice? Colorado's experiment with alternative transfer methods for water (ATMs). *Water Security*, **6**, 100027. https://doi.org/10.1016/j.wasec.2019.100027

203. Fulton, J., M. Norton, and F. Shilling, 2019: Water-indexed benefits and impacts of California almonds. *Ecological Indicators*, **96**, 711–717. https://doi.org/10.1016/j.ecolind.2017.12.063

204. Reisman, E., 2019: The great almond debate: A subtle double movement in California water. *Geoforum*, **104**, 137–146. https://doi.org/10.1016/j.geoforum.2019.04.021

205. Morgan, B., K. Spangler, J. Stuivenvolt Allen, C.N. Morrisett, M.W. Brunson, S.-Y.S. Wang, and N. Huntly, 2021: Water availability for cannabis in Northern California: Intersections of climate, policy, and public discourse. *Water*, **13** (1), 5. https://doi.org/10.3390/w13010005

206. Carney, M.A. and K.C. Krause, 2020: Immigration/migration and healthy publics: The threat of food insecurity. *Palgrave Communications*, **6** (1), 93. https://doi.org/10.1057/s41599-020-0461-0

207. Glazebrook, T., S. Noll, and E. Opoku, 2020: Gender matters: Climate change, gender bias, and women's farming in the global South and North. *Agriculture*, **10** (7), 267. https://doi.org/10.3390/agriculture10070267

208. Greene, C., 2018: Broadening understandings of drought—The climate vulnerability of farmworkers and rural communities in California (USA). *Environmental Science & Policy*, **89**, 283–291. https://doi.org/10.1016/j.envsci.2018.08.002

209. Howard, M., S. Ahmed, P. Lachapelle, and M.B. Schure, 2020: Farmer and rancher perceptions of climate change and their relationships with mental health. *Journal of Rural Mental Health*, **44** (2), 87–95. https://doi.org/10.1037/rmh0000131

210. Munden-Dixon, K., K. Tate, B. Cutts, and L. Roche, 2019: An uncertain future: Climate resilience of first-generation ranchers. *The Rangeland Journal*, **41**, 189–196. https://doi.org/10.1071/rj18023

211. Siegner, A., J. Sowerwine, and C. Acey, 2018: Does urban agriculture improve food security? Examining the nexus of food access and distribution of urban produced foods in the United States: A systematic review. *Sustainability*, **10** (9), 2988. https://doi.org/10.3390/su10092988

212. Adger, W.N., J. Barnett, K. Brown, N. Marshall, and K. O'Brien, 2013: Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, **3** (2), 112–117. https://doi.org/10.1038/nclimate1666

213. Hepler, M. and E.A. Kronk Warner, 2019: Learning from tribal innovations: Lessons in climate change adaptation. *Environmental Law Reporter*, **49** (11130). https://doi.org/10.2139/ssrn.3444403

214. Nabhan, G.P., E.C. Riordan, L. Monti, A.M. Rea, B.T. Wilder, E. Ezcurra, J.B. Mabry, J. Aronson, G.A. Barron-Gafford, J.M. García, A. Búrquez, T.E. Crews, P. Mirocha, and W.C. Hodgson, 2020: An Aridamerican model for agriculture in a hotter, water scarce world. *Plants, People, Planet*, **2** (6), 627–639. https://doi.org/10.1002/ppp3.10129

215. Sowerwine, J., D. Sarna-Wojcicki, M. Mucioki, L. Hillman, F. Lake, and E. Friedman, 2019: Enhancing food sovereignty: A five-year collaborative Tribal-University research and extension project in California and Oregon. *Journal of Agriculture, Food Systems, and Community Development*, **9** (B), 167–190. https://doi.org/10.5304/jafscd.2019.09b.013

216. Gosnell, H., S. Charnley, and P. Stanley, 2020: Climate change mitigation as a co-benefit of regenerative ranching: Insights from Australia and the United States. *Interface Focus*, **10** (5), 20200027. https://doi.org/10.1098/rsfs.2020.0027

217. Shrum, T.R., W.R. Travis, T.M. Williams, and E. Lih, 2018: Managing climate risks on the ranch with limited drought information. *Climate Risk Management*, **20**, 11–26. https://doi.org/10.1016/j.crm.2018.01.002

218. Mitchell, J.P., D.C. Reicosky, E.A. Kueneman, J. Fisher, and D. Beck, 2019: Conservation agriculture systems. *CABI Reviews*, **2019**, 1–25. https://doi.org/10.1079/pavsnnr201914001

219. Mpanga, I.K., G. Neumann, U.K. Schuch, and J. Schalau, 2020: Sustainable agriculture practices as a driver for increased harvested cropland among large-scale growers in Arizona: A paradox for small-scale growers. *Advanced Sustainable Systems*, **4** (4), 1900143. https://doi.org/10.1002/adsu.201900143

220. Kelly, C., S.J. Fonte, A. Shrestha, K.M. Daane, and J.P. Mitchell, 2021: Winter cover crops and no-till promote soil macrofauna communities in irrigated, Mediterranean cropland in California, USA. *Applied Soil Ecology*, **166**, 104068. https://doi.org/10.1016/j.apsoil.2021.104068

221. Paye, W.S., R. Ghimire, P. Acharya, A. Nilahyane, A.O. Mesbah, and M.A. Marsalis, 2022: Cover crop water use and corn silage production in semi-arid irrigated conditions. *Agricultural Water Management*, **260**, 107275. https://doi.org/10.1016/j.agwat.2021.107275

222. Thapa, V.R., R. Ghimire, D. VanLeeuwen, V. Acosta-Martínez, and M. Shukla, 2022: Response of soil organic matter to cover cropping in water-limited environments. *Geoderma*, **406**, 115497. https://doi.org/10.1016/j.geoderma.2021.115497

223. Babin, N., C. Klier, and A. Singh, 2022: Understanding and promoting adoption of irrigation efficiency practices in Paso Robles, California vineyards: The importance of farm typology and grower sustainability networks. *Current Research in Environmental Sustainability*, **4**, 100143. https://doi.org/10.1016/j.crsust.2022.100143

224. Douglass-Gallagher, E. and D. Stuart, 2019: Crop growers' adaptive capacity to climate change: A situated study of agriculture in Arizona's Verde Valley. *Environmental Management*, **63** (1), 94–109. https://doi.org/10.1007/s00267-018-1114-6

225. Johnson, M.K., A.M. Lien, N.R. Sherman, and L. López-Hoffman, 2018: Barriers to PES programs in Indigenous communities: A lesson in land tenure insecurity from the Hopi Indian reservation. *Ecosystem Services*, **32**, 62–69. https://doi.org/10.1016/j.ecoser.2018.05.009

226. Johnson, M.K., M.J. Rowe, A. Lien, and L. López-Hoffman, 2021: Enhancing integration of indigenous agricultural knowledge into USDA Natural Resources Conservation Service cost-share initiatives. *Journal of Soil and Water Conservation*, **76** (6), 487. https://doi.org/10.2489/jswc.2021.00179

227. MCDPH, 2021: Heat Reports. Maricopa County Department of Public Health, accessed August 15, 2022. https://www.maricopa.gov/1858/heat-surveillance

228. Putnam, H., D.M. Hondula, A. Urban, V. Berisha, P. Iñiguez, and M. Roach, 2018: It's not the heat, it's the vulnerability: Attribution of the 2016 spike in heat-associated deaths in Maricopa County, Arizona. *Environmental Research Letters*, **13** (9), 094022. https://doi.org/10.1088/1748-9326/aadb44

229. Schwarz, L., E.M. Castillo, T.C. Chan, J.J. Brennan, E.S. Sbiroli, G. Carrasco-Escobar, A. Nguyen, R.E.S. Clemesha, A. Gershunov, and T. Benmarhnia, 2022: Heat waves and emergency department visits among the homeless, San Diego, 2012–2019. *American Journal of Public Health*, **112** (1), 98–106. https://doi.org/10.2105/ajph.2021.306557

230. López-Carr, D., J. Vanos, A. Sánchez-Vargas, R. Vargas, and F. Castillo, 2022: Extreme heat and COVID-19: A dual burden for farmworkers. *Frontiers in Public Health*, **10**, 884152. https://doi.org/10.3389/fpubh.2022.884152

231. Méndez, M., G. Flores-Haro, and L. Zucker, 2020: The (in)visible victims of disaster: Understanding the vulnerability of undocumented Latino/a and Indigenous immigrants. *Geoforum*, **116**, 50–62. https://doi.org/10.1016/j.geoforum.2020.07.007

232. Mitchell, D.C., J. Castro, T.L. Armitage, A.J. Vega-Arroyo, S.C. Moyce, D.J. Tancredi, D.H. Bennett, J.H. Jones, T. Kjellstrom, and M.B. Schenker, 2017: Recruitment, methods, and descriptive results of a physiologic assessment of Latino farmworkers: The California heat illness prevention study. *Journal of Occupational and Environmental Medicine*, **59** (7). https://doi.org/10.1097/jom.0000000000000988

233. Taylor, E.V., A. Vaidyanathan, W.D. Flanders, M. Murphy, M. Spencer, and R.S. Noe, 2018: Differences in heat-related mortality by citizenship status: United States, 2005–2014. *American Journal of Public Health*, **108** (S2), S131–S136. https://doi.org/10.2105/ajph.2017.304006

234. Guardaro, M., D.M. Hondula, J. Ortiz, and C.L. Redman, 2022: Adaptive capacity to extreme urban heat: The dynamics of differing narratives. *Climate Risk Management*, **35**, 100415. https://doi.org/10.1016/j.crm.2022.100415

235. Jay, O., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, and K.L. Ebi, 2021: Reducing the health effects of hot weather and heat extremes: From personal cooling strategies to green cities. *The Lancet*, **398** (10301), 709–724. https://doi.org/10.1016/s0140-6736(21)01209-5

236. CDC, 2022: National Environmental Public Health Tracking Network. Centers for Disease Control and Prevention, accessed August 20, 2022. https://ephtracking.cdc.gov/dataexplorer/

237. Avalos, L.A., H. Chen, D.-K. Li, and R. Basu, 2017: The impact of high apparent temperature on spontaneous preterm delivery: A case-crossover study. *Environmental Health*, **16** (1), 5. https://doi.org/10.1186/s12940-017-0209-5

238. Barreca, A. and J. Schaller, 2020: The impact of high ambient temperatures on delivery timing and gestational lengths. *Nature Climate Change*, **10** (1), 77–82. https://doi.org/10.1038/s41558-019-0632-4

239. Ilango, S.D., M. Weaver, P. Sheridan, L. Schwarz, R.E.S. Clemesha, T. Bruckner, R. Basu, A. Gershunov, and T. Benmarhnia, 2020: Extreme heat episodes and risk of preterm birth in California, 2005–2013. *Environment International*, **137**, 105541. https://doi.org/10.1016/j.envint.2020.105541

240. Lu, C., Y. Zhang, B. Li, Z. Zhao, C. Huang, X. Zhang, H. Qian, J. Wang, W. Liu, Y. Sun, D. Norbäck, and Q. Deng, 2022: Interaction effect of prenatal and postnatal exposure to ambient air pollution and temperature on childhood asthma. *Environment International*, **167**, 107456. https://doi.org/10.1016/j.envint.2022.107456

241. Gershunov, A. and K. Guirguis, 2012: California heat waves in the present and future. *Geophysical Research Letters*, **39** (18). https://doi.org/10.1029/2012gl052979

242. EPA, 2021: Climate Change Indicators: Health and Society. U.S. Environmental Protection Agency. https://www.epa.gov/climate-indicators/health-society

243. Prein, A.F., G.J. Holland, R.M. Rasmussen, M.P. Clark, and M.R. Tye, 2016: Running dry: The U.S. Southwest's drift into a drier climate state. *Geophysical Research Letters*, **43** (3), 1272–1279. https://doi.org/10.1002/2015gl066727

244. Achakulwisut, P., S.C. Anenberg, J.E. Neumann, S.L. Penn, N. Weiss, A. Crimmins, N. Fann, J. Martinich, H. Roman, and L.J. Mickley, 2019: Effects of increasing aridity on ambient dust and public health in the U.S. Southwest under climate change. *GeoHealth*, **3** (5), 127–144. https://doi.org/10.1029/2019gh000187

245. McCotter, O.Z., K. Benedict, D.M. Engelthaler, K. Komatsu, K.D. Lucas, J.C. Mohle-Boetani, H. Oltean, D. Vugia, T.M. Chiller, G.L. Sondermeyer Cooksey, A. Nguyen, C.C. Roe, C. Wheeler, and R. Sunenshine, 2019: Update on the Epidemiology of coccidioidomycosis in the United States. *Medical Mycology*, **57** (Supplement_1), S30–S40. https://doi.org/10.1093/mmy/myy095

246. Gorris, M.E., L.A. Cat, C.S. Zender, K.K. Treseder, and J.T. Randerson, 2018: Coccidioidomycosis dynamics in relation to climate in the southwestern United States. *GeoHealth*, **2** (1), 6–24. https://doi.org/10.1002/2017gh000095

247. Head, J.R., G. Sondermeyer-Cooksey, A.K. Heaney, A.T. Yu, I. Jones, A. Bhattachan, S.K. Campo, R. Wagner, W. Mgbara, S. Phillips, N. Keeney, J. Taylor, E. Eisen, D.P. Lettenmaier, A. Hubbard, G.S. Okin, D.J. Vugia, S. Jain, and J.V. Remais, 2022: Effects of precipitation, heat, and drought on incidence and expansion of coccidioidomycosis in western USA: A longitudinal surveillance study. *The Lancet Planetary Health*, **6** (10), e793–e803. https://doi.org/10.1016/s2542-5196(22)00202-9

248. Gorris, M.E., J.E. Neumann, P.L. Kinney, M. Sheahan, and M.C. Sarofim, 2021: Economic valuation of coccidioidomycosis (Valley fever) projections in the United States in response to climate change. *Weather, Climate, and Society*, **13** (1), 107–123. https://doi.org/10.1175/wcas-d-20-0036.1

249. Graff Zivin, J. and M. Neidell, 2014: Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics*, **32** (1), 1–26. https://doi.org/10.1086/671766

250. Vanos, J., S. Moyce, B. Lemke, and T. Kjellstrom, 2021: Ch. 10. Extreme heat exposure and occupational health in a changing climate. In: *Extreme Events and Climate Change: A Multidisciplinary Approach*. Castillo, F., M. Wehner, and D.A. Stone, Eds. Wiley, 147–166. https://doi.org/10.1002/9781119413738.ch10

251. Zhang, Y. and D.T. Shindell, 2021: Costs from labor losses due to extreme heat in the USA attributable to climate change. *Climatic Change*, **164** (3), 35. https://doi.org/10.1007/s10584-021-03014-2

252. Castillo, F., A.M. Mora, G.L. Kayser, J. Vanos, C. Hyland, A.R. Yang, and B. Eskenazi, 2021: Environmental health threats to Latino migrant farmworkers. *Annual Review of Public Health*, **42** (1), 257–276. https://doi.org/10.1146/annurev-publhealth-012420-105014

253. Stevens, A.W., 2017: Temperature, Wages, and Agricultural Labor Productivity. University of California, Berkeley. https://www.econ.iastate.edu/files/events/files/stevens_jmp_jan16.pdf

254. Moyce, S., J. Joseph, D. Tancredi, D. Mitchell, and M. Schenker, 2016: Cumulative incidence of acute kidney injury in California's agricultural workers. *Journal of Occupational and Environmental Medicine*, **58** (4). https://doi.org/10.1097/jom.0000000000000668

255. Wesseling, C., J. Glaser, J. Rodríguez-Guzmán, I. Weiss, R. Lucas, S. Peraza, A. Soares da Silva, E. Hansson, R.J. Johnson, C. Hogstedt, D.H. Wegman, and K. Jakobsson, 2020: Chronic kidney disease of non-traditional origin in Mesoamerica: A disease primarily driven by occupational heat stress. *Pan American Journal of Public Health*, **44**, 15. https://doi.org/10.26633/rpsp.2020.15

256. Foster, J., J.W. Smallcombe, S. Hodder, O. Jay, A.D. Flouris, and G. Havenith, 2022: Quantifying the impact of heat on human physical work capacity; Part II: The observed interaction of air velocity with temperature, humidity, sweat rate, and clothing is not captured by most heat stress indices. *International Journal of Biometeorology*, **66** (3), 507–520. https://doi.org/10.1007/s00484-021-02212-y

257. Foster, J., J.W. Smallcombe, S. Hodder, O. Jay, A.D. Flouris, L. Nybo, and G. Havenith, 2021: An advanced empirical model for quantifying the impact of heat and climate change on human physical work capacity. *International Journal of Biometeorology*, **65** (7), 1215–1229. https://doi.org/10.1007/s00484-021-02105-0

258. Foster, J., J.W. Smallcombe, S. Hodder, O. Jay, A.D. Flouris, L. Nybo, and G. Havenith, 2022: Quantifying the impact of heat on human physical work capacity; Part III: The impact of solar radiation varies with air temperature, humidity, and clothing coverage. *International Journal of Biometeorology*, **66** (1), 175–188. https://doi.org/10.1007/s00484-021-02205-x

259. Smallcombe, J.W., J. Foster, S.G. Hodder, O. Jay, A.D. Flouris, and G. Havenith, 2022: Quantifying the impact of heat on human physical work capacity; part IV: Interactions between work duration and heat stress severity. *International Journal of Biometeorology*, **66** (12), 2463–2476. https://doi.org/10.1007/s00484-022-02370-7

260. Colmer, J., I. Hardman, J. Shimshack, and J. Voorheis, 2020: Disparities in $PM_{2.5}$ air pollution in the United States. *Science*, **369** (6503), 575–578. https://doi.org/10.1126/science.aaz9353

261. Liang, Y., D. Sengupta, M.J. Campmier, D.M. Lunderberg, J.S. Apte, and A.H. Goldstein, 2021: Wildfire smoke impacts on indoor air quality assessed using crowdsourced data in California. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (36), e2106478118. https://doi.org/10.1073/pnas.2106478118

262. Navarro, K.M., R. Cisneros, D. Schweizer, P. Chowdhary, E.M. Noth, J.R. Balmes, and S.K. Hammond, 2019: Incident command post exposure to polycyclic aromatic hydrocarbons and particulate matter during a wildfire. *Journal of Occupational and Environmental Hygiene*, **16** (11), 735–744. https://doi.org/10.1080/15459624.2019.1657579

263. Fann, N., B. Alman, R.A. Broome, G.G. Morgan, F.H. Johnston, G. Pouliot, and A.G. Rappold, 2018: The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012. *Science of The Total Environment*, **610–611**, 802–809. https://doi.org/10.1016/j.scitotenv.2017.08.024

264. Yang, X., Y. Yu, S. Shirowzhan, S. sepasgozar, and H. Li, 2020: Automated PPE-tool pair check system for construction safety using smart IoT. *Journal of Building Engineering*, **32**, 101721. https://doi.org/10.1016/j.jobe.2020.101721

265. Aguilera, R., T. Corringham, A. Gershunov, and T. Benmarhnia, 2021: Wildfire smoke impacts respiratory health more than fine particles from other sources: Observational evidence from Southern California. *Nature Communications*, **12** (1), 1493. https://doi.org/10.1038/s41467-021-21708-0

266. Jaffe, D.A., S.M. O'Neill, N.K. Larkin, A.L. Holder, D.L. Peterson, J.E. Halofsky, and A.G. Rappold, 2020: Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air & Waste Management Association*, **70** (6), 583–615. https://doi.org/10.1080/10962247.2020.1749731

267. Grant, E. and J.D. Runkle, 2022: Long-term health effects of wildfire exposure: A scoping review. *The Journal of Climate Change and Health*, **6**, 100110. https://doi.org/10.1016/j.joclim.2021.100110

268. Silveira, S., M. Kornbluh, M.C. Withers, G. Grennan, V. Ramanathan, and J. Mishra, 2021: Chronic mental health sequelae of climate change extremes: A case study of the deadliest Californian wildfire. *International Journal of Environmental Research and Public Health*, **18** (4), 1487. https://doi.org/10.3390/ijerph18041487

269. Proctor, C.R., J. Lee, D. Yu, A.D. Shah, and A.J. Whelton, 2020: Wildfire caused widespread drinking water distribution network contamination. AWWA *Water Science*, **2** (4), e1183. https://doi.org/10.1002/aws2.1183

270. National Academies of Sciences, Engineering, and Medicine, 2020: *Implications of the California Wildfires for Health, Communities, and Preparedness: Proceedings of a Workshop*. The National Academies Press, Washington, DC. https://doi.org/10.17226/25622

271. Dong, L., L.R. Leung, J. Lu, and Y. Gao, 2019: Contributions of extreme and non-extreme precipitation to California precipitation seasonality changes under warming. *Geophysical Research Letters*, **46** (22), 13470–13478. https://doi.org/10.1029/2019gl084225

272. Huang, X. and D.L. Swain, 2022: Climate change is increasing the risk of a California megaflood. *Science Advances*, **8** (32), 0995. https://doi.org/10.1126/sciadv.abq0995

273. Semenza, J.C., J. Rocklöv, and K.L. Ebi, 2022: Climate change and cascading risks from infectious disease. *Infectious Diseases and Therapy*, **11** (4), 1371–1390. https://doi.org/10.1007/s40121-022-00647-3

274. NCEZID, 2023: 2022 Provisional Human Data. Centers for Disease Control and Prevention, National Center for Emerging and Zoonotic Infectious Diseases, accessed April 3, 2023. https://wwwn.cdc.gov/arbonet/maps/adb_diseases_map/index.html

275. CA DWR, 2022: Central Valley Flood Protection Plan Update 2022. State of California, Natural Resources Agency, Department of Water Resources. https://water.ca.gov/-/media/dwr-website/web-pages/programs/flood-management/flood-planning-and-studies/central-valley-flood-protection-plan/files/cvfpp-updates/2022/central_valley_flood_protection_plan_update_2022_adopted.pdf

276. Gorris, M.E., A.W. Bartlow, S.D. Temple, D. Romero-Alvarez, D.P. Shutt, J.M. Fair, K.A. Kaufeld, S.Y. Del Valle, and C.A. Manore, 2021: Updated distribution maps of predominant *Culex* mosquitoes across the Americas. *Parasites & Vectors*, **14** (1), 547. https://doi.org/10.1186/s13071-021-05051-3

277. Méndez, M., 2022: Behind the bougainvillea curtain: Wildfires and inequality. *Issues in Science and Technology*, **38** (2), 84–90. https://www.preventionweb.net/publication/behind-bougainvillea-curtain-wildfires-and-inequality

278. CBP, 2020: Southwest Border Migration FY 2020. U.S. Customs and Border Protection. https://www.cbp.gov/newsroom/stats/sw-border-migration-fy2020

279. WFP, 2017: Food Security and Emigration: Why People Flee and the Impact on Family Members Left Behind in El Salvador, Guatemala, and Honduras. United Nations World Food Programme. https://docs.wfp.org/api/documents/wfp-0000019632/download/

280. Bradatan, C., J.A. Dennis, N. Flores-Yeffal, and S. Swain, 2020: Child health, household environment, temperature and rainfall anomalies in Honduras: A socio-climate data linked analysis. *Environmental Health*, **19** (1), 10. https://doi.org/10.1186/s12940-020-0560-9

281. U.S. Census Bureau, 2021: Community Resilience Estimates: Thematic Risk Factor (RF). U.S. Department of Commerce, U.S. Census Bureau. https://experience.arcgis.com/experience/b0341fa9b237456c9a9f1758c15cde8d/

282. U.S. Census Bureau, 2023: Selected Population Profile in the United States—2021: ACS 1-Year Estimates Selected Population Profiles. U.S. Department of Commerce, U.S. Census Bureau, accessed April 3, 2023. https://data.census.gov/table?q=united+states&t=716:720:721:722&g=040xx00us04,06,08,32,35,49&y=2021

283. Schwerdtle, P., K. Bowen, and C. McMichael, 2018: The health impacts of climate-related migration. *BMC Medicine*, **16** (1), 1. https://doi.org/10.1186/s12916-017-0981-7

284. White-Newsome, J., S. McCormick, N. Sampson, M. Buxton, M. O'Neill, C. Gronlund, L. Catalano, K. Conlon, and E. Parker, 2014: Strategies to reduce the harmful effects of extreme heat events: A four-city study. *International Journal of Environmental Research and Public Health*, **11** (2), 1960–1988. https://doi.org/10.3390/ijerph110201960

285. NCEH, 2015: CDC's Building Resilience Against Climate Effects (BRACE) Framework. Centers for Disease Control and Prevention, National Center for Environmental Health. https://www.cdc.gov/climateandhealth/brace.htm

286. Shortridge, A., W. Walker Vi, D.D. White, M.M. Guardaro, D.M. Hondula, and J.K. Vanos, 2022: HeatReady schools: A novel approach to enhance adaptive capacity to heat through school community experiences, risks, and perceptions. *Climate Risk Management*, **36**, 100437. https://doi.org/10.1016/j.crm.2022.100437

287. ADHS, 2021: Managing Extreme Heat Recommendations for Schools: Pilot Version. Arizona Department of Health Services, Phoenix, AZ. https://www.azdhs.gov/documents/preparedness/epidemiology-disease-control/extreme-weather/heat/managing-extreme-heat-recommendations-for-schools.pdf

288. NCEH, 2020: Preparing for the Regional Health Impacts of Climate Change in the United States: A Summary of Health Effects, Resources, and Adaptation Examples from Health Departments Funded by CDC's Climate and Health Program. Centers for Disease Control and Prevention, National Center for Environmental Health. https://stacks.cdc.gov/view/cdc/99147

289. Rosenthal, N., T. Benmarhnia, R. Ahmadov, E. James, and M.E. Marlier, 2022: Population co-exposure to extreme heat and wildfire smoke pollution in California during 2020. *Environmental Research: Climate*, **1** (2), 025004. https://doi.org/10.1088/2752-5295/ac860e

290. Stowell, J.D., C.-E. Yang, J.S. Fu, N.C. Scovronick, M.J. Strickland, and Y. Liu, 2022: Asthma exacerbation due to climate change-induced wildfire smoke in the western US. *Environmental Research Letters*, **17** (1), 014023. https://doi.org/10.1088/1748-9326/ac4138

291. The World Bank, 2021: Enabling Private Investment in Climate Adaptation & Resilience. World Bank Group. https://openknowledge.worldbank.org/server/api/core/bitstreams/127de8c7-d367-59ac-9e54-27ee52c744aa/content

292. CDI, 2023: Climate Risk Carbon Initiative. California Department of Insurance. https://www.insurance.ca.gov/0250-insurers/0300-insurers/0100-applications/ci/

293. Margolis, E.Q., C.H. Guiterman, R.D. Chavardès, J.D. Coop, K. Copes-Gerbitz, D.A. Dawe, D.A. Falk, J.D. Johnston, E. Larson, H. Li, J.M. Marschall, C.E. Naficy, A.T. Naito, M.-A. Parisien, S.A. Parks, J. Portier, H.M. Poulos, K.M. Robertson, J.H. Speer, M. Stambaugh, T.W. Swetnam, A.J. Tepley, I. Thapa, C.D. Allen, Y. Bergeron, L.D. Daniels, P.Z. Fulé, D. Gervais, M.P. Girardin, G.L. Harley, J.E. Harvey, K.M. Hoffman, J.M. Huffman, M.D. Hurteau, L.B. Johnson, C.W. Lafon, M.K. Lopez, R.S. Maxwell, J. Meunier, M. North, M.T. Rother, M.R. Schmidt, R.L. Sherriff, L.A. Stachowiak, A. Taylor, E.J. Taylor, V. Trouet, M.L. Villarreal, L.L. Yocom, K.B. Arabas, A.H. Arizpe, D. Arseneault, A.A. Tarancón, C. Baisan, E. Bigio, F. Biondi, G.D. Cahalan, A. Caprio, J. Cerano-Paredes, B.M. Collins, D.C. Dey, I. Drobyshev, C. Farris, M.A. Fenwick, W. Flatley, M.L. Floyd, Z.e. Gedalof, A. Holz, L.F. Howard, D.W. Huffman, J. Iniguez, K.F. Kipfmueller, S.G. Kitchen, K. Lombardo, D. McKenzie, A.G. Merschel, K.L. Metlen, J. Minor, C.D. O'Connor, L. Platt, W.J. Platt, T. Saladyga, A.B. Stan, S. Stephens, C. Sutheimer, R. Touchan, and P.J. Weisberg, 2022: The North American tree-ring fire-scar network. *Ecosphere*, **13** (7), e4159. https://doi.org/10.1002/ecs2.4159

294. Guiterman, C.H., R.M. Gregg, L.A.E. Marshall, J.J. Beckmann, P.J. van Mantgem, D.A. Falk, J.E. Keeley, A.C. Caprio, J.D. Coop, P.J. Fornwalt, C. Haffey, R.K. Hagmann, S.T. Jackson, A.M. Lynch, E.Q. Margolis, C. Marks, M.D. Meyer, H. Safford, A.D. Syphard, A. Taylor, C. Wilcox, D. Carril, C.A.F. Enquist, D. Huffman, J. Iniguez, N.A. Molinari, C. Restaino, and J.T. Stevens, 2022: Vegetation type conversion in the US Southwest: Frontline observations and management responses. *Fire Ecology*, **18** (1), 6. https://doi.org/10.1186/s42408-022-00131-w

295. Hagmann, R.K., P.F. Hessburg, S.J. Prichard, N.A. Povak, P.M. Brown, P.Z. Fulé, R.E. Keane, E.E. Knapp, J.M. Lydersen, K.L. Metlen, M.J. Reilly, A.J. Sánchez Meador, S.L. Stephens, J.T. Stevens, A.H. Taylor, L.L. Yocom, M.A. Battaglia, D.J. Churchill, L.D. Daniels, D.A. Falk, P. Henson, J.D. Johnston, M.A. Krawchuk, C.R. Levine, G.W. Meigs, A.G. Merschel, M.P. North, H.D. Safford, T.W. Swetnam, and A.E.M. Waltz, 2021: Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecological Applications*, **31** (8), e02431. https://doi.org/10.1002/eap.2431

296. Lake, F.K., J. Parrotta, C.P. Giardina, I. Davidson-Hunt, and Y. Uprety, 2018: Ch. 12. Integration of Traditional and Western knowledge in forest landscape restoration. In: *Forest Landscape Restoration: Integrated Approaches to Support Effective Implementation*. Mansourian, S. and J. Parrotta, Eds. Routledge, New York, 198–226. https://www.fs.usda.gov/treesearch/pubs/57158

297. Collins, L., H. Clarke, M.F. Clarke, S.C. McColl Gausden, R.H. Nolan, T. Penman, and R. Bradstock, 2022: Warmer and drier conditions have increased the potential for large and severe fire seasons across south-eastern Australia. *Global Ecology and Biogeography*, **31** (10), 1933–1948. https://doi.org/10.1111/geb.13514

298. Coop, J.D., S.A. Parks, C.S. Stevens-Rumann, S.D. Crausbay, P.E. Higuera, M.D. Hurteau, A. Tepley, E. Whitman, T. Assal, B.M. Collins, K.T. Davis, S. Dobrowski, D.A. Falk, P.J. Fornwalt, P.Z. Fulé, B.J. Harvey, V.R. Kane, C.E. Littlefield, E.Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K.C. Rodman, 2020: Wildfire-driven forest conversion in western North American landscapes. *BioScience*, **70** (8), 659–673. https://doi.org/10.1093/biosci/biaa061

299. North, M.P., R.E. Tompkins, A.A. Bernal, B.M. Collins, S.L. Stephens, and R.A. York, 2022: Operational resilience in western US frequent-fire forests. *Forest Ecology and Management*, **507**, 120004. https://doi.org/10.1016/j.foreco.2021.120004

300. Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, R.E. Keane, L.N. Kobziar, C.A. Kolden, M. North, S.A. Parks, H.D. Safford, J.T. Stevens, L.L. Yocom, D.J. Churchill, R.W. Gray, D.W. Huffman, F.K. Lake, and P. Khatri-Chhetri, 2021: Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications*, **31** (8), e02433. https://doi.org/10.1002/eap.2433

301. MacDonald, G., T. Wall, C.A.F. Enquist, S.R. LeRoy, J.B. Bradford, D.D. Breshears, T. Brown, D. Cayan, C. Dong, D.A. Falk, E. Fleishman, A. Gershunov, M. Hunter, R.A. Loehman, P.J. van Mantgem, B.R. Middleton, H.D. Safford, M.W. Schwartz, and V. Trouet, 2023: Drivers of California's changing wildfires: A state-of-the-knowledge synthesis. *International Journal of Wildland Fire*, **32** (7), 1039–1058. https://doi.org/10.1071/WF22155

302. Westerling, A.L., 2016: Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371** (1696), 20150178. https://doi.org/10.1098/rstb.2015.0178

303. Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam, 2006: Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, **313** (5789), 940–943. https://doi.org/10.1126/science.1128834

304. CalFire, 2021: Top 20 Deadliest California Wildfires. California Department of Forestry and Fire Protection. https://www.fire.ca.gov/our-impact/statistics

305. NICC, 2021: Wildland Fire Summary and Statistics Annual Report 2020. National Interagency Coordination Center. https://www.predictiveservices.nifc.gov/intelligence/intelligence.htm

306. NICC, 2022: Wildland Fire Summary and Statistics Annual Report 2021. National Interagency Coordination Center. https://www.predictiveservices.nifc.gov/intelligence/intelligence.htm

307. Stinnesbeck, J., 2020: Wildfires in Nevada: An Overview. Legislative Counsel Bureau, Research Division, 5 pp. https://www.leg.state.nv.us/division/research/documents/wildfires-in-nevada-2020-final.pdf

308. Li, Z., J.P. Angerer, and X.B. Wu, 2021: Temporal patterns of large wildfires and their burn severity in rangelands of western United States. *Geophysical Research Letters*, **48** (7), e2020GL091636. https://doi.org/10.1029/2020GL091636

309. Archer, D., D. Toledo, D.M. Blumenthal, J. Derner, C. Boyd, K. Davies, E. Hamerlynck, R. Sheley, P. Clark, S. Hardegree, F. Pierson, C. Clements, B. Newingham, B. Rector, J. Gaskin, C.L. Wonkka, K. Jensen, T. Monaco, L.T. Vermeire, and S.L. Young, 2023: Invasive annual grasses—Reenvisioning approaches in a changing climate. *Journal of Soil and Water Conservation*, **78** (2), 95–103. https://doi.org/10.2489/jswc.2023.00074

310. Singleton, M.P., A.E. Thode, A.J. Sánchez Meador, and J.M. Iniguez, 2019: Increasing trends in high-severity fire in the southwestern USA from 1984 to 2015. *Forest Ecology and Management*, **433**, 709–719. https://doi.org/10.1016/j.foreco.2018.11.039

311. Haffey, C., T.D. Sisk, C.D. Allen, A.E. Thode, and E.Q. Margolis, 2018: Limits to ponderosa pine regeneration following large high-severity forest fires in the United States Southwest. *Fire Ecology*, **14** (1), 143–163. https://doi.org/10.4996/fireecology.140114316

312. Webb, A.D., D.A. Falk, and D.M. Finch, 2019: Fire Ecology and Management in Lowland Riparian Ecosystems of the Southwestern United States and Northern Mexico. Gen. Tech. Rep. RMRS-GTR-401. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 132 pp. https://www.fs.usda.gov/research/treesearch/59156

313. Davis, K.T., S.Z. Dobrowski, P.E. Higuera, Z.A. Holden, T.T. Veblen, M.T. Rother, S.A. Parks, A. Sala, and M.P. Maneta, 2019: Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6193–6198. https://doi.org/10.1073/pnas.1815107116

314. O'Connor, R.C., M.J. Germino, D.M. Barnard, C.M. Andrews, J.B. Bradford, D.S. Pilliod, R.S. Arkle, and R.K. Shriver, 2020: Small-scale water deficits after wildfires create long-lasting ecological impacts. *Environmental Research Letters*, **15** (4), 044001. https://doi.org/10.1088/1748-9326/ab79e4

315. Rodman, K.C., T.T. Veblen, M.A. Battaglia, M.E. Chambers, P.J. Fornwalt, Z.A. Holden, T.E. Kolb, J.R. Ouzts, and M.T. Rother, 2020: A changing climate is snuffing out post-fire recovery in montane forests. *Global Ecology and Biogeography*, **29** (11), 2039–2051. https://doi.org/10.1111/geb.13174

316. Parks, S.A., S.Z. Dobrowski, J.D. Shaw, and C. Miller, 2019: Living on the edge: Trailing edge forests at risk of fire-facilitated conversion to non-forest. *Ecosphere*, **10** (3), e02651. https://doi.org/10.1002/ecs2.2651

317. Halofsky, J.E., D.L. Peterson, and B.J. Harvey, 2020: Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, **16** (1), 4. https://doi.org/10.1186/s42408-019-0062-8

318. Keeley, J.E. and A.D. Syphard, 2019: Twenty-first century California, USA, wildfires: Fuel-dominated vs. wind-dominated fires. *Fire Ecology*, **15** (1), 24. https://doi.org/10.1186/s42408-019-0041-0

319. Loehman, R.A., R.E. Keane, and L.M. Holsinger, 2020: Simulation modeling of complex climate, wildfire, and vegetation dynamics to address wicked problems in land management. *Frontiers in Forests and Global Change*, **3**, 3. https://doi.org/10.3389/ffgc.2020.00003

320. Stevens-Rumann, C.S., K.B. Kemp, P.E. Higuera, B.J. Harvey, M.T. Rother, D.C. Donato, P. Morgan, and T.T. Veblen, 2018: Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters*, **21** (2), 243–252. https://doi.org/10.1111/ele.12889

321. Stevens-Rumann, C.S. and P. Morgan, 2019: Tree regeneration following wildfires in the western US: A review. *Fire Ecology*, **15** (1), 15. https://doi.org/10.1186/s42408-019-0032-1

322. Turner, M.G., K.H. Braziunas, W.D. Hansen, and B.J. Harvey, 2019: Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (23), 11319–11328. https://doi.org/10.1073/pnas.1902841116

323. Doherty, K., D.M. Theobald, J.B. Bradford, L.A. Wiechman, G. Bedrosian, C.S. Boyd, M. Cahill, P.S. Coates, M.K. Creutzburg, M.R. Crist, S.P. Finn, A.V. Kumar, C.E. Littlefield, J.D. Maestas, K.L. Prentice, B.G. Prochazka, T.E. Remington, W.D. Sparklin, J.C. Tull, Z. Wurtzebach, and K.A. Zeller, 2022: A Sagebrush Conservation Design to Proactively Restore America's Sagebrush Biome. Open-File Report 2022–1081. U.S. Geological Survey. https://www.usgs.gov/publications/a-sagebrush-conservation-design-proactively-restore-americas-sagebrush-biome

324. Shinneman, D.J., E.K. Strand, M. Pellant, J.T. Abatzoglou, M.W. Brunson, N.F. Glenn, J.A. Heinrichs, M. Sadegh, and N.M. Vaillant, 2023: Future direction of fuels management in sagebrush rangelands. *Rangeland Ecology & Management*, **86**, 50–63. https://doi.org/10.1016/j.rama.2022.10.009

325. Felton, A.J., R.K. Shriver, M. Stemkovski, J.B. Bradford, K.N. Suding, and P.B. Adler, 2022: Climate disequilibrium dominates uncertainty in long-term projections of primary productivity. *Ecology Letters*, **25** (12), 2688–2698. https://doi.org/10.1111/ele.14132

326. Ellis, T.M., D.M.J.S. Bowman, P. Jain, M.D. Flannigan, and G.J. Williamson, 2022: Global increase in wildfire risk due to climate-driven declines in fuel moisture. *Global Change Biology*, **28** (4), 1544–1559. https://doi.org/10.1111/gcb.16006

327. Haynes, K., K. Short, G. Xanthopoulos, D. Viegas, L.M. Ribeiro, and R. Blanchi, 2020: Wildfires and WUI fire fatalities. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Manzello, S.L., Ed. Springer, Cham, Switzerland, 1–16. https://doi.org/10.1007/978-3-319-51727-8_92-1

328. Schwarz, L., A. Dimitrova, R. Aguilera, R. Basu, A. Gershunov, and T. Benmarhnia, 2022: Smoke and COVID-19 case fatality ratios during California wildfires. *Environmental Research Letters*, **17** (1), 014054. https://doi.org/10.1088/1748-9326/ac4538

329. Tiwari, B., B. Ajmera, A. Gonzalez, and H. Sonbol, 2020: Impact of wildfire on triggering mudslides—A case study of 2018 Montecito debris flows. In: *Geo-Congress 2020: Engineering, Monitoring, and Management of Geotechnical Infrastructure*. Hambleton, J.P., R. Makhnenko, and A.S. Budge, Eds. American Society of Civil Engineers, Reston, VA, 40–49. https://doi.org/10.1061/9780784482797.005

330. Murray, A.T., L. Carvalho, R.L. Church, C. Jones, D. Roberts, J. Xu, K. Zigner, and D. Nash, 2021: Coastal vulnerability under extreme weather. *Applied Spatial Analysis and Policy*, **14** (3), 497–523. https://doi.org/10.1007/s12061-020-09357-0

331. Radeloff, V.C., D.P. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar-Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, and S.I. Stewart, 2018: Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (13), 3314–3319. https://doi.org/10.1073/pnas.1718850115

332. Rao, K., A.P. Williams, N.S. Diffenbaugh, M. Yebra, and A.G. Konings, 2022: Plant-water sensitivity regulates wildfire vulnerability. *Nature Ecology & Evolution*, **6** (3), 332–339. https://doi.org/10.1038/s41559-021-01654-2

333. Zhuang, Y., R. Fu, B.D. Santer, R.E. Dickinson, and A. Hall, 2021: Quantifying contributions of natural variability and anthropogenic forcings on increased fire weather risk over the western United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (45), e2111875118. https://doi.org/10.1073/pnas.2111875118

334. Winkler, R.L. and M.D. Rouleau, 2021: Amenities or disamenities? Estimating the impacts of extreme heat and wildfire on domestic US migration. *Population and Environment*, **42** (4), 622–648. https://doi.org/10.1007/s11111-020-00364-4

335. Sharygin, E., 2021: Ch. 3. Estimating migration impacts of wildfire: California's 2017 North Bay fires. In: *The Demography of Disasters: Impacts for Population and Place*. Karácsonyi, D., A. Taylor, and D. Bird, Eds. Springer, Cham, Switzerland, 49–70. https://doi.org/10.1007/978-3-030-49920-4_3

336. Baijnath-Rodino, J.A., M. Kumar, M. Rivera, K.D. Tran, and T. Banerjee, 2021: How vulnerable are American states to wildfires? A livelihood vulnerability assessment. *Fire*, **4** (3), 54. https://doi.org/10.3390/fire4030054

337. Goldsmith, L., V. Raditz, and M. Méndez, 2022: Queer and present danger: Understanding the disparate impacts of disasters on LGBTQ+ communities. *Disasters*, **46** (4), 946–973. https://doi.org/10.1111/disa.12509

338. Davies, I.P., R.D. Haugo, J.C. Robertson, and P.S. Levin, 2018: The unequal vulnerability of communities of color to wildfire. *PLoS ONE*, **13** (11), 0205825. https://doi.org/10.1371/journal.pone.0205825

339. Engelman, A., L. Craig, and A. Iles, 2022: Global disability justice in climate disasters: Mobilizing people with disabilities as change agents. *Health Affairs*, **41** (10), 1496–1504. https://doi.org/10.1377/hlthaff.2022.00474

340. Madhusoodanan, J., 2021: Wildfires pose a burning problem for wines and winemakers. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (34), e2113327118. https://doi.org/10.1073/pnas.2113327118

341. Cartier, E.A. and L.L. Taylor, 2020: Living in a wildfire: The relationship between crisis management and community resilience in a tourism-based destination. *Tourism Management Perspectives*, **34**, 100635. https://doi.org/10.1016/j.tmp.2020.100635

342. Kim, M.-K. and P.M. Jakus, 2019: Wildfire, national park visitation, and changes in regional economic activity. *Journal of Outdoor Recreation and Tourism*, **26**, 34–42. https://doi.org/10.1016/j.jort.2019.03.007

343. Dillis, C., V. Butsic, D. Moanga, P. Parker-Shames, A. Wartenberg, and T.E. Grantham, 2022: The threat of wildfire is unique to cannabis among agricultural sectors in California. *Ecosphere*, **13** (9), e4205. https://doi.org/10.1002/ecs2.4205

344. Crews, P., P. Dorenbach, G. Amberchan, R.F. Keiffer, I. Lizama-Chamu, T.C. Ruthenburg, E.P. McCauley, and G. McGourty, 2022: Natural product phenolic diglycosides created from wildfires, defining their impact on California and Oregon grapes and wines. *Journal of Natural Products*, **85** (3), 547–561. https://doi.org/10.1021/acs.jnatprod.2c00028

345. Rhoades, C.C., J.P. Nunes, U. Silins, and S.H. Doerr, 2019: The influence of wildfire on water quality and watershed processes: New insights and remaining challenges. *International Journal of Wildland Fire*, **28** (10), 721–725. https://doi.org/10.1071/wfv28n10_fo

346. Carbone, L.M., J. Tavella, J.G. Pausas, and R. Aguilar, 2019: A global synthesis of fire effects on pollinators. *Global Ecology and Biogeography*, **28** (10), 1487–1498. https://doi.org/10.1111/geb.12939

347. O'Hara, K.C., J. Ranches, L.M. Roche, T.K. Schohr, R.C. Busch, and G.U. Maier, 2021: Impacts from wildfires on livestock health and production: Producer perspectives. *Animals*, **11** (11), 3230. https://doi.org/10.3390/ani11113230

348. Gellman, J., M. Walls, and M. Wibbenmeyer, 2022: Wildfire, smoke, and outdoor recreation in the western United States. *Forest Policy and Economics*, **134**, 102619. https://doi.org/10.1016/j.forpol.2021.102619

349. Vukomanovic, J. and T. Steelman, 2019: A systematic review of relationships between mountain wildfire and ecosystem services. *Landscape Ecology*, **34** (5), 1179–1194. https://doi.org/10.1007/s10980-019-00832-9

350. Hohner, A.K., C.C. Rhoades, P. Wilkerson, and F.L. Rosario-Ortiz, 2019: Wildfires alter forest watersheds and threaten drinking water quality. *Accounts of Chemical Research*, **52** (5), 1234–1244. https://doi.org/10.1021/acs.accounts.8b00670

351. Schulze, S.S., E.C. Fischer, S. Hamideh, and H. Mahmoud, 2020: Wildfire impacts on schools and hospitals following the 2018 California Camp Fire. *Natural Hazards*, **104** (1), 901–925. https://doi.org/10.1007/s11069-020-04197-0

352. Robinne, F.-N., D.W. Hallema, K.D. Bladon, M.D. Flannigan, G. Boisramé, C.M. Bréthaut, S.H. Doerr, G. Di Baldassarre, L.A. Gallagher, A.K. Hohner, S.J. Khan, A.M. Kinoshita, R. Mordecai, J.P. Nunes, P. Nyman, C. Santín, G. Sheridan, C.R. Stoof, M.P. Thompson, J.M. Waddington, and Y. Wei, 2021: Scientists' warning on extreme wildfire risks to water supply. *Hydrological Processes*, **35** (5), e14086. https://doi.org/10.1002/hyp.14086

353. Juliano, T.W., P.A. Jiménez, B. Kosović, T. Eidhammer, G. Thompson, L.K. Berg, J. Fast, A. Motley, and A. Polidori, 2022: Smoke from 2020 United States wildfires responsible for substantial solar energy forecast errors. *Environmental Research Letters*, **17** (3), 034010. https://doi.org/10.1088/1748-9326/ac5143

354. Pereira, P., I. Bogunovic, W. Zhao, and D. Barcelo, 2021: Short-term effect of wildfires and prescribed fires on ecosystem services. *Current Opinion in Environmental Science & Health*, **22**, 100266. https://doi.org/10.1016/j.coesh.2021.100266

355. van Mantgem, P.J., A.C. Caprio, N.L. Stephenson, and A.J. Das, 2021: Forest resistance to extended drought enhanced by prescribed fire in low elevation forests of the Sierra Nevada. *Forests*, **12** (9), 1248. https://doi.org/10.3390/f12091248

356. Hunter, M.E. and M.D. Robles, 2020: Tamm review: The effects of prescribed fire on wildfire regimes and impacts: A framework for comparison. *Forest Ecology and Management*, **475**, 118435. https://doi.org/10.1016/j.foreco.2020.118435

357. Long, J.W., F.K. Lake, R.W. Goode, and B.M. Burnette, 2020: How traditional tribal perspectives influence ecosystem restoration. *Ecopsychology*, **12** (2). https://doi.org/10.1089/eco.2019.0055

358. Banerjee, T., 2020: Impacts of forest thinning on wildland fire behavior. *Forests*, **11** (9), 918. https://doi.org/10.3390/f11090918

359. Goodwin, M.J., M.P. North, H.S.J. Zald, and M.D. Hurteau, 2020: Changing climate reallocates the carbon debt of frequent-fire forests. *Global Change Biology*, **26** (11), 6180–6189. https://doi.org/10.1111/gcb.15318

360. Stephens, S.L., M.A. Battaglia, D.J. Churchill, B.M. Collins, M. Coppoletta, C.M. Hoffman, J.M. Lydersen, M.P. North, R.A. Parsons, S.M. Ritter, and J.T. Stevens, 2021: Forest restoration and fuels reduction: Convergent or divergent? *BioScience*, **71** (1), 85–101. https://doi.org/10.1093/biosci/biaa134

361. Striplin, R., S.A. McAfee, H.D. Safford, and M.J. Papa, 2020: Retrospective analysis of burn windows for fire and fuels management: An example from the Lake Tahoe Basin, California, USA. *Fire Ecology*, **16** (1), 13. https://doi.org/10.1186/s42408-020-00071-3

362. Sleeter, B.M., D.C. Marvin, D.R. Cameron, P.C. Selmants, A.L. Westerling, J. Kreitler, C.J. Daniel, J. Liu, and T.S. Wilson, 2019: Effects of 21st-century climate, land use, and disturbances on ecosystem carbon balance in California. *Global Change Biology*, **25** (10), 3334–3353. https://doi.org/10.1111/gcb.14677

363. Xu, X., A. Huang, E. Belle, P. De Frenne, and G. Jia, 2022: Protected areas provide thermal buffer against climate change. *Science Advances*, **8** (44), 0119. https://doi.org/10.1126/sciadv.abo0119

364. Anderegg, W.R.L., A.T. Trugman, G. Badgley, C.M. Anderson, A. Bartuska, P. Ciais, D. Cullenward, C.B. Field, J. Freeman, S.J. Goetz, J.A. Hicke, D. Huntzinger, R.B. Jackson, J. Nickerson, S. Pacala, and J.T. Randerson, 2020: Climate-driven risks to the climate mitigation potential of forests. *Science*, **368** (6497), 7005. https://doi.org/10.1126/science.aaz7005

365. Ontl, T.A., M.K. Janowiak, C.W. Swanston, J. Daley, S. Handler, M. Cornett, S. Hagenbuch, C. Handrick, L. McCarthy, and N. Patch, 2020: Forest management for carbon sequestration and climate adaptation. *Journal of Forestry*, **118** (1), 86–101. https://doi.org/10.1093/jofore/fvz062

366. Krofcheck, D.J., C.C. Remy, A.R. Keyser, and M.D. Hurteau, 2019: Optimizing forest management stabilizes carbon under projected climate and wildfires. *Journal of Geophysical Research: Biogeosciences*, **124** (10), 3075–3087. https://doi.org/10.1029/2019jg005206

367. North, M.P., J.T. Stevens, D.F. Greene, M. Coppoletta, E.E. Knapp, A.M. Latimer, C.M. Restaino, R.E. Tompkins, K.R. Welch, R.A. York, D.J.N. Young, J.N. Axelson, T.N. Buckley, B.L. Estes, R.N. Hager, J.W. Long, M.D. Meyer, S.M. Ostoja, H.D. Safford, K.L. Shive, C.L. Tubbesing, H. Vice, D. Walsh, C.M. Werner, and P. Wyrsch, 2019: Tamm review: Reforestation for resilience in dry western U.S. forests. *Forest Ecology and Management*, **432**, 209–224. https://doi.org/10.1016/j.foreco.2018.09.007

368. Holl, K.D. and P.H.S. Brancalion, 2020: Tree planting is not a simple solution. *Science*, **368** (6491), 580–581. https://doi.org/10.1126/science.aba8232

369. Anderson, R., P.E. Bayer, and D. Edwards, 2020: Climate change and the need for agricultural adaptation. *Current Opinion in Plant Biology*, **56**, 197–202. https://doi.org/10.1016/j.pbi.2019.12.006

370. Meyer, M.D., B.L. Estes, A. Wuenschel, B. Bulaon, A. Stucy, D.F. Smith, and A.C. Caprio, 2019: Structure, diversity and health of Sierra Nevada red fir forests with reestablished fire regimes. *International Journal of Wildland Fire*, **28** (5), 386–396. https://doi.org/10.1071/wf18114

371. Mildenberger, M., P.D. Howe, S. Trachtman, L.C. Stokes, and M. Lubell, 2022: The effect of public safety power shut-offs on climate change attitudes and behavioural intentions. *Nature Energy*, **7** (8), 736–743. https://doi.org/10.1038/s41560-022-01071-0

372. Zanocco, C., J. Flora, R. Rajagopal, and H. Boudet, 2021: When the lights go out: Californians' experience with wildfire-related public safety power shutoffs increases intention to adopt solar and storage. *Energy Research & Social Science*, **79**, 102183. https://doi.org/10.1016/j.erss.2021.102183

373. Mildenberger, M., S. Trachtman, P. Howe, L. Stokes, and M. Lubell, 2021: Wildfire-mitigating power shut-offs promote household-level adaptation but not climate policy support. *Nature Portfolio*. https://doi.org/10.21203/rs.3.rs-631250/v1

374. Wong-Parodi, G., 2020: When climate change adaptation becomes a "looming threat" to society: Exploring views and responses to California wildfires and public safety power shutoffs. *Energy Research & Social Science*, **70**, 101757. https://doi.org/10.1016/j.erss.2020.101757

375. Martin, J.T., G.T. Pederson, C.A. Woodhouse, E.R. Cook, G.J. McCabe, K.J. Anchukaitis, E.K. Wise, P.J. Erger, L. Dolan, M. McGuire, S. Gangopadhyay, K.J. Chase, J.S. Littell, S.T. Gray, S. St. George, J.M. Friedman, D.J. Sauchyn, J.-M. St-Jacques, and J. King, 2020: Increased drought severity tracks warming in the United States' largest river basin. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (21), 11328–11336. https://doi.org/10.1073/pnas.1916208117

376. Luo, X., S. Dee, S. Stevenson, Y. Okumura, N. Steiger, and L. Parsons, 2022: Last millennium ENSO diversity and North American teleconnections: New insights from paleoclimate data assimilation. *Paleoceanography and Paleoclimatology*, **37** (3), e2021PA004283. https://doi.org/10.1029/2021pa004283

377. Patricola, C.M., J.P. O'Brien, M.D. Risser, A.M. Rhoades, T.A. O'Brien, P.A. Ullrich, D.A. Stone, and W.D. Collins, 2020: Maximizing ENSO as a source of western US hydroclimate predictability. *Climate Dynamics*, **54** (1), 351–372. https://doi.org/10.1007/s00382-019-05004-8

378. Brown, T.C., V. Mahat, and J.A. Ramirez, 2019: Adaptation to future water shortages in the United States caused by population growth and climate change. *Earth's Future*, **7** (3), 219–234. https://doi.org/10.1029/2018ef001091

379. Di Baldassarre, G., N. Wanders, A. AghaKouchak, L. Kuil, S. Rangecroft, T.I.E. Veldkamp, M. Garcia, P.R. van Oel, K. Breinl, and A.F. Van Loon, 2018: Water shortages worsened by reservoir effects. *Nature Sustainability*, **1** (11), 617–622. https://doi.org/10.1038/s41893-018-0159-0

380. Elias, E., J. Reyes, C. Steele, and A. Rango, 2018: Diverse landscapes, diverse risks: Synthesis of the special issue on climate change and adaptive capacity in a hotter, drier Southwestern United States. *Climatic Change*, **148** (3), 339–353. https://doi.org/10.1007/s10584-018-2219-x

381. Zhang, F., J.A. Biederman, M.P. Dannenberg, D. Yan, S.C. Reed, and W.K. Smith, 2021: Five decades of observed daily precipitation reveal longer and more variable drought events across much of the western United States. *Geophysical Research Letters*, **48** (7), e2020GL092293. https://doi.org/10.1029/2020gl092293

382. du Bray, M.V., B. Quimby, J.C. Bausch, A. Wutich, W.M. Eaton, K.J. Brasier, A. Brewis, and C. Williams, 2022: Red, white, and blue: Environmental distress among water stakeholders in a U.S. farming community. *Weather, Climate, and Society*, **14** (2), 585–595. https://doi.org/10.1175/wcas-d-21-0103.1

383. Wilson, N.J., T. Montoya, R. Arseneault, and A. Curley, 2021: Governing water insecurity: Navigating Indigenous water rights and regulatory politics in settler colonial states. *Water International*, **46** (6), 783–801. https://doi.org/10.1080/02508060.2021.1928972

384. Wutich, A., W. Jepson, C. Velasco, A. Roque, Z. Gu, M. Hanemann, M.J. Hossain, L. Landes, R. Larson, W.W. Li, O. Morales-Pate, N. Patwoary, S. Porter, Y.-s. Tsai, M. Zheng, and P. Westerhoff, 2022: Water insecurity in the Global North: A review of experiences in U.S. colonias communities along the Mexico border. *WIREs Water*, **9** (4), e1595. https://doi.org/10.1002/wat2.1595

385. Laufkötter, C., J. Zscheischler, and T.L. Frölicher, 2020: High-impact marine heatwaves attributable to human-induced global warming. *Science*, **369** (6511), 1621–1625. https://doi.org/10.1126/science.aba0690

386. Orr, J.A., R.D. Vinebrooke, M.C. Jackson, K.J. Kroeker, R.L. Kordas, C. Mantyka-Pringle, P.J. Van den Brink, F. De Laender, R. Stoks, M. Holmstrup, C.D. Matthaei, W.A. Monk, M.R. Penk, S. Leuzinger, R.B. Schäfer, and J.J. Piggott, 2020: Towards a unified study of multiple stressors: Divisions and common goals across research disciplines. *Proceedings of the Royal Society B: Biological Sciences*, **287** (1926), 20200421. https://doi.org/10.1098/rspb.2020.0421

387. Sunday, J.M., E. Howard, S. Siedlecki, D.J. Pilcher, C. Deutsch, P. MacCready, J. Newton, and T. Klinger, 2022: Biological sensitivities to high-resolution climate change projections in the California Current Marine Ecosystem. *Global Change Biology*, **28** (19), 5726–5740. https://doi.org/10.1111/gcb.16317

388. National Academies of Sciences, Engineering, and Medicine, 2022: *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*. The National Academies Press, Washington, DC, 322 pp. https://doi.org/10.17226/26278

389. DeAngelo, J., B.T. Saenz, I.B. Arzeno-Soltero, C.A. Frieder, M.C. Long, J. Hamman, K.A. Davis, and S.J. Davis, 2023: Economic and biophysical limits to seaweed farming for climate change mitigation. *Nature Plants*, **9** (1), 45–57. https://doi.org/10.1038/s41477-022-01305-9

390. Levin, L.A., J.M. Alfaro-Lucas, A. Colaço, E.E. Cordes, N. Craik, R. Danovaro, H.-J. Hoving, J. Ingels, N.C. Mestre, S. Seabrook, A.R. Thurber, C. Vivian, and M. Yasuhara, 2023: Deep-sea impacts of climate interventions. *Science*, **379** (6636), 978–981. https://doi.org/10.1126/science.ade7521

391. Spillias, S., R. Kelly, R.S. Cottrell, K.R. O'Brien, R.-Y. Im, J.Y. Kim, C. Lei, R.W.S. Leung, M. Matsuba, J.A. Reis, Y. Sato, K. Sempert, and E. McDonald-Madden, 2023: The empirical evidence for the social-ecological impacts of seaweed farming. *PLOS Sustainability and Transformation*, **2** (2), e0000042. https://doi.org/10.1371/journal.pstr.0000042

392. Gobler, C.J., 2020: Climate change and harmful algal blooms: Insights and perspective. *Harmful Algae*, **91**, 101731. https://doi.org/10.1016/j.hal.2019.101731

393. Sea-Level Rise Leadership Team, 2022: State Agency Sea-Level Rise Action Plan for California. State of California, Ocean Protection Council. https://www.opc.ca.gov/webmaster/_media_library/2022/02/Item-7_Exhibit-A_SLR-Action-Plan-Final.pdf

394. State of California, 2022: Protecting Californians from Extreme Heat: A State Action Plan to Build Community Resilience. State of California. https://resources.ca.gov/-/media/CNRA-Website/Files/Initiatives/Climate-Resilience/2022-Final-Extreme-Heat-Action-Plan.pdf

395. State of California, 2021: California Climate Adaptation Strategy. State of California. https://climateresilience.ca.gov/

396. Governor's Office of Planning and Research, 2022: Climate Adaptation Planning Grant Program. State of California, Governor's Office of Planning and Research. https://opr.ca.gov/climate/icarp/grants/adaptation-planning-grant.html#:~:text=The%20Adaptation%20Planning%20Grant%20Program,infrastructure%20projects%20across%20the%20state

397. Caltrans, 2022: Climate Adaptation Planning—Sustainable Transportation Planning Grant Program. California Department of Transportation. https://www.grants.ca.gov/grants/climate-adaptation-planning-sustainable-transportation-planning-grant-program/

398. California Transportation Commission, 2022: Local Transportation Climate Adaptation Program (LTCAP). State of California, California Transportation Commission. https://catc.ca.gov/programs/local-transportation-climate-adaptation-program

399. Governor's Office of Planning and Research, 2022: Regional Resilience Planning and Implementation Grant Program. State of California, Governor's Office of Planning and Research. https://opr.ca.gov/climate/icarp/grants/regional-resilience-grant.html

400. Lester, S.E., R.R. Gentry, H.R. Lemoine, H.E. Froehlich, L.D. Gardner, M. Rennick, E.O. Ruff, and K.D. Thompson, 2022: Diverse state-level marine aquaculture policy in the United States: Opportunities and barriers for industry development. *Reviews in Aquaculture*, **14** (2), 890–906. https://doi.org/10.1111/raq.12631

401. Froehlich, H.E., J.Z. Koehn, K.K. Holsman, and B.S. Halpern, 2022: Emerging trends in science and news of climate change threats to and adaptation of aquaculture. *Aquaculture*, **549**, 737812. https://doi.org/10.1016/j.aquaculture.2021.737812

402. Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, J.T. Abatzoglou, K. Bolles, S.H. Baek, A.M. Badger, and B. Livneh, 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368** (6488), 314–318. https://doi.org/10.1126/science.aaz9600

403. Dannenberg, M.P., D. Yan, M.L. Barnes, W.K. Smith, M.R. Johnston, R.L. Scott, J.A. Biederman, J.F. Knowles, X. Wang, T. Duman, M.E. Litvak, J.S. Kimball, A.P. Williams, and Y. Zhang, 2022: Exceptional heat and atmospheric dryness amplified losses of primary production during the 2020 U.S. Southwest hot drought. *Global Change Biology*, **28** (16), 4794–4806. https://doi.org/10.1111/gcb.16214

404. Robertson, A.D., Y. Zhang, L.A. Sherrod, S.T. Rosenzweig, L. Ma, L. Ahuja, and M.E. Schipanski, 2018: Climate change impacts on yields and soil carbon in row crop dryland agriculture. *Journal of Environmental Quality*, **47** (4), 684–694. https://doi.org/10.2134/jeq2017.08.0309

405. Collier, R.J., L.H. Baumgard, R.B. Zimbelman, and Y. Xiao, 2018: Heat stress: Physiology of acclimation and adaptation. *Animal Frontiers*, **9** (1), 12–19. https://doi.org/10.1093/af/vfy031

406. Klemm, T. and D.D. Briske, 2021: Retrospective assessment of beef cow numbers to climate variability throughout the U.S. Great Plains. *Rangeland Ecology & Management*, **78**, 273–280. https://doi.org/10.1016/j.rama.2019.07.004

407. Schwarz, L., K. Hansen, A. Alari, S.D. Ilango, N. Bernal, R. Basu, A. Gershunov, and T. Benmarhnia, 2021: Spatial variation in the joint effect of extreme heat events and ozone on respiratory hospitalizations in California. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (22), e2023078118. https://doi.org/10.1073/pnas.2023078118

408. Georgescu, M., P.E. Morefield, B.G. Bierwagen, and C.P. Weaver, 2014: Urban adaptation can roll back warming of emerging megapolitan regions. *Proceedings of the National Academy of Sciences of the United States of America*, **111** (8), 2909–2914. https://doi.org/10.1073/pnas.1322280111

409. Hondula, D.M., M. Georgescu, and R.C. Balling, 2014: Challenges associated with projecting urbanization-induced heat-related mortality. *Science of The Total Environment*, **490**, 538–544. https://doi.org/10.1016/j.scitotenv.2014.04.130

410. Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara, 2021: The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2011048118. https://doi.org/10.1073/pnas.2011048118

411. Magzamen, S., R.W. Gan, J. Liu, K. O'Dell, B. Ford, K. Berg, K. Bol, A. Wilson, E.V. Fischer, and J.R. Pierce, 2021: Differential cardiopulmonary health impacts of local and long-range transport of wildfire smoke. *GeoHealth*, **5** (3), 2020GH000330. https://doi.org/10.1029/2020gh000330

412. Hondula, D.M., J.L. Sabo, R. Quay, M. Chester, M. Georgescu, N.B. Grimm, S.L. Harlan, A. Middel, S. Porter, C.L. Redman, B. Rittmann, B.L. Ruddell, and D.D. White, 2019: Cities of the Southwest are testbeds for urban resilience. *Frontiers in Ecology and the Environment*, **17** (2), 79–80. https://doi.org/10.1002/fee.2005

413. Keith, L. and S. Meerow, 2022: Planning for Urban Heat Resilience. PAS Report 600. American Planning Association, 99 pp. https://www.planning.org/publications/report/9245695/

414. Keith, L., S. Meerow, D.M. Hondula, V.K. Turner, and J.C. Arnott, 2021: Deploy heat officers, policies and metrics. *Nature*, **598** (7879), 29–31. https://doi.org/10.1038/d41586-021-02677-2

415. Schramm, P.J., A.L.A. Janabi, L.W. Campbell, J.L. Donatuto, and S.C. Gaughen, 2020: How Indigenous communities are adapting to climate change: Insights from the Climate-Ready Tribes Initiative. *Health Affairs*, **39** (12), 2153–2159. https://doi.org/10.1377/hlthaff.2020.00997

416. OPHDST, 2023: National Notifiable Disease Surveillance System: Notifiable Infectious Disease Tables. Centers for Disease Control and Prevention, Office of Public Health Data, Surveillance, and Technology. https://www.cdc.gov/nndss/data-statistics/infectious-tables/index.html

417. Rochlin, I., A. Faraji, K. Healy, and T.G. Andreadis, 2019: West Nile virus mosquito vectors in North America. *Journal of Medical Entomology*, **56** (6), 1475–1490. https://doi.org/10.1093/jme/tjz146

418. Reisen, W.K., 2012: The contrasting bionomics of *Culex* mosquitoes in western North America. *Journal of the American Mosquito Control Association*, **28** (4s), 82–91. https://doi.org/10.2987/8756-971x-28.4.82

419. Harrigan, R.J., H.A. Thomassen, W. Buermann, and T.B. Smith, 2014: A continental risk assessment of West Nile virus under climate change. *Global Change Biology*, **20** (8), 2417–2425. https://doi.org/10.1111/gcb.12534

420. Habeeb, D., J. Vargo, and B. Stone, 2015: Rising heat wave trends in large US cities. *Natural Hazards*, **76** (3), 1651–1665. https://doi.org/10.1007/s11069-014-1563-z

421. Ebi, K.L., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, and O. Jay, 2021: Hot weather and heat extremes: Health risks. *The Lancet*, **398** (10301), 698–708. https://doi.org/10.1016/s0140-6736(21)01208-3

422. Crooks, J.L., W.E. Cascio, M.S. Percy, J. Reyes, L.M. Neas, and E.D. Hilborn, 2016: The association between dust storms and daily non-accidental mortality in the United States, 1993–2005. *Environmental Health Perspectives*, **124** (11), 1735–1743. https://doi.org/10.1289/ehp216

423. Reid, C.E., E.M. Considine, G.L. Watson, D. Telesca, G.G. Pfister, and M. Jerrett, 2019: Associations between respiratory health and ozone and fine particulate matter during a wildfire event. *Environment International*, **129**, 291–298. https://doi.org/10.1016/j.envint.2019.04.033

424. Borlina, C.S. and N.O. Rennó, 2017: The impact of a severe drought on dust lifting in California's Owens Lake area. *Scientific Reports*, **7** (1), 1784. https://doi.org/10.1038/s41598-017-01829-7

425. U.S. Census Bureau, 2022: Foreign Born. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/topics/population/foreign-born.html

426. Reid, C.E. and M.M. Maestas, 2019: Wildfire smoke exposure under climate change: Impact on respiratory health of affected communities. *Current Opinion in Pulmonary Medicine*, **25** (2). https://doi.org/10.1097/mcp.0000000000000552

427. Bekkar, B., S. Pacheco, R. Basu, and N. DeNicola, 2020: Association of air pollution and heat exposure with preterm birth, low birth weight, and stillbirth in the US: A systematic review. *JAMA Network Open*, **3** (6), e208243. https://doi.org/10.1001/jamanetworkopen.2020.8243

428. Benmarhnia, T., J. Huang, R. Basu, J. Wu, and T.A. Bruckner, 2017: Decomposition analysis of Black–White disparities in birth outcomes: The relative contribution of air pollution and social factors in California. *Environmental Health Perspectives*, **125** (10), 107003. https://doi.org/10.1289/ehp490

429. Lowe, A.A., B. Bender, A.H. Liu, T. Solomon, A. Kobernick, W. Morgan, and L.B. Gerald, 2018: Environmental concerns for children with asthma on the Navajo Nation. *Annals of the American Thoracic Society*, **15** (6), 745–753. https://doi.org/10.1513/annalsats.201708-674ps

430. Sun, Y., S.D. Ilango, L. Schwarz, Q. Wang, J.-C. Chen, J.M. Lawrence, J. Wu, and T. Benmarhnia, 2020: Examining the joint effects of heatwaves, air pollution, and green space on the risk of preterm birth in California. *Environmental Research Letters*, **15** (10), 104099. https://doi.org/10.1088/1748-9326/abb8a3

431. USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp. https://doi.org/10.7930/j0r49nqx

432. Ebi, K.L., J. Vanos, J.W. Baldwin, J.E. Bell, D.M. Hondula, N.A. Errett, K. Hayes, C.E. Reid, S. Saha, J. Spector, and P. Berry, 2021: Extreme weather and climate change: Population health and health system implications. *Annual Review of Public Health*, **42** (1), 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

433. Dennison, P.E., S.C. Brewer, J.D. Arnold, and M.A. Moritz, 2014: Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters*, **41** (8), 2928–2933. https://doi.org/10.1002/2014gl059576

434. Parks, S.A. and J.T. Abatzoglou, 2020: Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters*, **47** (22), e2020GL089858. https://doi.org/10.1029/2020gl089858

435. Kitzberger, T., D.A. Falk, A.L. Westerling, and T.W. Swetnam, 2017: Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. *PLoS ONE*, **12** (12), e0188486. https://doi.org/10.1371/journal.pone.0188486

436. Hurteau, M. and M. North, 2008: Mixed-conifer understory response to climate change, nitrogen, and fire. *Global Change Biology*, **14** (7), 1543–1552. https://doi.org/10.1111/j.1365-2486.2008.01584.x

437. Hurteau, M.D., S. Liang, A.L. Westerling, and C. Wiedinmyer, 2019: Vegetation-fire feedback reduces projected area burned under climate change. *Scientific Reports*, **9** (1), 2838. https://doi.org/10.1038/s41598-019-39284-1

438. Littell, J.S., 2018: Drought and fire in the western USA: Is climate attribution enough? *Current Climate Change Reports*, **4** (4), 396–406. https://doi.org/10.1007/s40641-018-0109-y

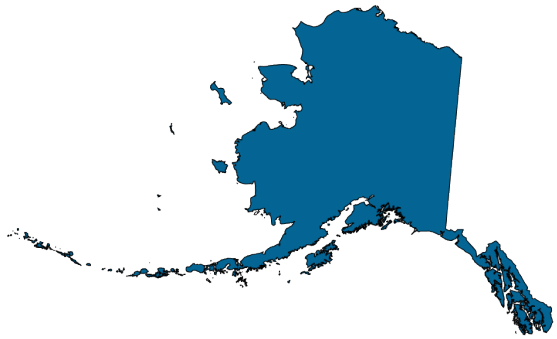
439. Stowell, J.D., G. Geng, E. Saikawa, H.H. Chang, J. Fu, C.-E. Yang, Q. Zhu, Y. Liu, and M.J. Strickland, 2019: Associations of wildfire smoke $PM_{2.5}$ exposure with cardiorespiratory events in Colorado 2011–2014. *Environment International*, **133**, 105151. https://doi.org/10.1016/j.envint.2019.105151

440. Dixon, L., F. Tsang, and G. Fitts, 2018: The Impact of Changing Wildfire Risk on California's Residential Insurance Market. California's Fourth Climate Change Assessment. CCCA4-CNRA-2018-008. California Natural Resources Agency. https://www.energy.ca.gov/sites/default/files/2019-12/Forests_CCCA4-CNRA-2018-008_ada.pdf

441. Wang, D., D. Guan, S. Zhu, M.M. Kinnon, G. Geng, Q. Zhang, H. Zheng, T. Lei, S. Shao, P. Gong, and S.J. Davis, 2021: Economic footprint of California wildfires in 2018. *Nature Sustainability*, **4** (3), 252–260. https://doi.org/10.1038/s41893-020-00646-7

Fifth National Climate Assessment: Chapter 29

# Alaska



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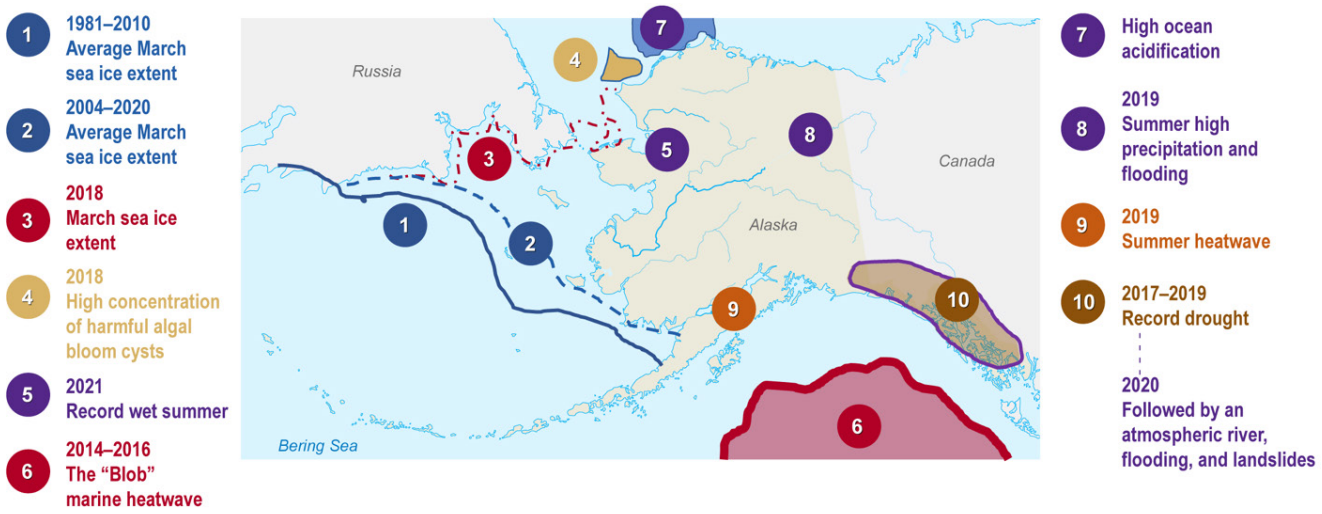
# Introduction

Alaska is warming two to three times faster than the global average.[1,2] The physical and ecological effects of warming are evident around the state (Figures 29.1, 29.11). Glaciers are shrinking, permafrost is thawing, and sea ice is diminishing. The growing season is longer, and fish, mammals, birds, and insects have increased in numbers in some areas and dropped sharply in others. This combination of environmental effects has far-reaching consequences for people statewide. Following a brief description of distinctive characteristics of Alaska and an overview of recent climatology in this Introduction, the chapter emphasizes the societal implications of climate change for Alaska to a greater degree than in the corresponding chapters of previous National Climate Assessments (NCAs), with illustrative examples and recurring themes, such as salmon, governance, and adaptation.

## Recent Climate-Driven Extremes and Notable Events




**Climate-driven extreme events continue throughout Alaska.**

**Figure 29.1.** Climate-driven extremes and notable events have recently affected different regions of Alaska. These events have redefined expectations of regional extremes and challenged preparedness (Focus on Compound Events). March sea ice extent in 2018 was far below recent low averages (Figure A4.6).[3] High concentrations of harmful algal bloom cysts were discovered in the Chukchi Sea (KM 29.1).[4] A record wet summer occurred in northwest Alaska in 2021, and 2019 brought uncharacteristic precipitation and flooding on the North Slope. The effects of the 2014–2016 North Pacific marine heatwave (the "Blob")[5] have become clear (Figures 29.11, A4.11; Box 10.1). Ongoing ocean acidification in Arctic Alaska has contributed to fundamental changes in marine water quality (KM 3.4).[6] In summer 2019, a record and persistent heatwave occurred in southern Alaska. A multiyear drought (2017–2019)[7,8] in Southeast Alaska's rainforest was followed by intense rain and destructive landslides.[9] Figure credit: USGS, NOAA Fisheries, and Ocean Conservancy.

Climatologically, Alaska is notable for frozen water in the forms of permafrost, sea ice, land ice, and snow. Culturally, Alaska is home to 21 distinct Indigenous Peoples, comprising about one-fifth of the population. Alaska's lands and communities are governed by a complex system of federal, state, and local agencies and 229 Tribal governments, as well as Alaska Native regional and village corporations. More than 200 communities are located off the road system. Most of these have year-round access by only small aircraft and summer access by ferry, cargo barge, or river vessel. Economically, Alaska is dominated by the public sector and by natural resource industries, with fisheries being the largest private-sector industry in terms of employment and oil and gas the largest in terms of revenue.[10] These characteristics shape the ways that climate change affects society in Alaska (see also KM 29.2).

Responses to climate change in Alaska's communities occur in the context of the governance systems divided among federal, state, regional, local, and Tribal agencies, with various and often overlapping responsibilities. About two-thirds of Alaska's land is under federal jurisdiction, with another quarter owned by the State of Alaska and a tenth owned by Alaska Native corporations. Tribal governments, with few exceptions, do not have geographical jurisdiction but are responsible for many programs affecting Tribal members. Because climate change affects society in many ways, fragmented governance can frustrate a coordinated response or the ability of communities to address climate change in a holistic fashion (Figure 29.16). Some precedents, such as the Denali Commission (an independent federal agency designed to provide Alaska with critical utilities, infrastructure, and economic support), demonstrate the potential for greater coordination of government support to better address community needs, if adequate resources and direction are provided.

Since NCA4 was published in 2018, Alaska has continued to experience rapid, widespread, and extreme climate-related changes in the form of ocean warming, record low sea ice,[3,11,12] the world's highest rates of ocean acidification,[6,13] an increasing frequency of extreme events such as marine heatwaves (KM 10.1),[5,12,14,15] and extreme snow and rain storms in winter (App. 4.2; Box 29.2).[16,17] These changes have reduced biological productivity, shifted seasonal timing of productivity, altered food web dynamics, and caused steep declines in prey.[18,19,20,21] In many freshwater environments, these changes result in a combination of reduced summer streamflows, increased summer water temperatures, hypoxia, and decreased prey abundance, which are lethal to many aquatic species.[7,19,22,23] There is no indication that these trends will slow or reverse in the near future (KM 2.2).[19,24,25,26,27,28,29]

Climate change in Alaska is driven by global trends (KM 2.1), but regional impacts are evident. The state is experiencing warming air temperatures,[1] record-breaking droughts,[7] reduced snowpack,[1] shrinking glaciers,[30,31] continued permafrost thaw,[32] relative sea level change,[33] record numbers of pollen outbreaks, increasingly destructive wildfires,[34] changing snowfall amounts and seasons,[1] and changing patterns of windstorms.[35] Although year-to-year variability is and will be a feature of Alaska's climate,[36] it is apparent that detectable warming trends started in the 1970s.[1,2] Annual average temperatures have increased across the state since 1971, with increases ranging from 2.4°F in Southeast Alaska to 6.2°F in northern Alaska,[1] up to 2.6 times the rate of change in the Lower 48. Of the annual average Alaska warming for 1950–2017, 75% is explained by greenhouse gas warming.[37] Heatwaves are increasing in the Arctic.[38] A 2019 summer heatwave brought record-high temperatures to southern and Interior Alaska,[39] with daily high temperatures exceeding normal by more than 20°F. This event had important community impacts such as wildfire smoke and fish kills, as well as uncharacteristically severe and expensive disturbances such as the Swan Lake Fire on the Kenai Peninsula.[40] Alaska's statewide annual average surface air temperature is projected to increase by 8.1°F (4.5°C) by the end of the century under an intermediate scenario (SSP2-4.5) and 14.2°F (7.9°C) under a very high scenario (SSP5-8.5), for 2081–2100 relative to 1981–2010.[41,42] This projection is 2.5°F (1.4°C) greater than comparable regional projections in NCA4.[43]

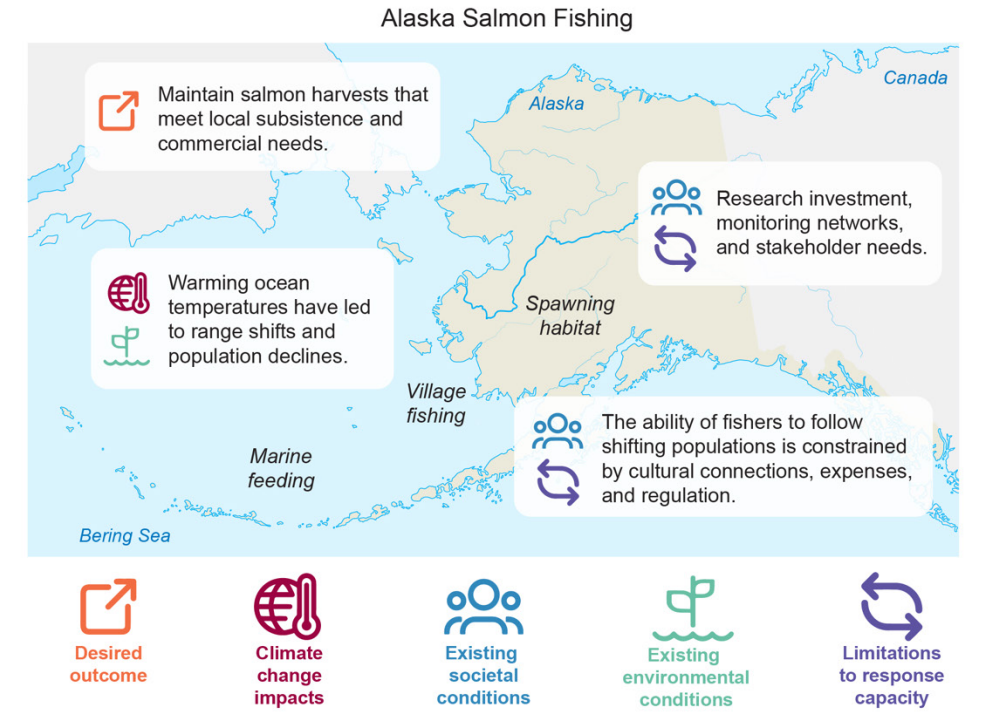
Annual and seasonal precipitation totals are generally increasing, but the size and significance of the changes vary with dataset and location,[1,44] with the most consistent increasing trends in northern Alaska, particularly on the North Slope (over 2.5% per decade).[1] One- and five-day maximum precipitation is increasing in most Alaska climate divisions, but changes are statistically significant since 1957 on the North Slope (over 2% per decade) and in the southeastern part of the Interior (over 1.4% per decade). Recent unprecedented extreme rainfall and seasonal precipitation events have presented challenges in multiple parts of Alaska. For example, an atmospheric river (an atmospheric flow that causes extreme precipitation) in December 2020 broke all-time extreme 24-hour precipitation records in 11 Southeast Alaska communities and caused two fatalities and more than $33.5 million (in 2022 dollars) in public property damage due to rain-on-snow and storm runoff as well as wind and landslides. Alaska's statewide average annual total precipitation is projected to increase by 20.6% by the end of the century under an intermediate scenario

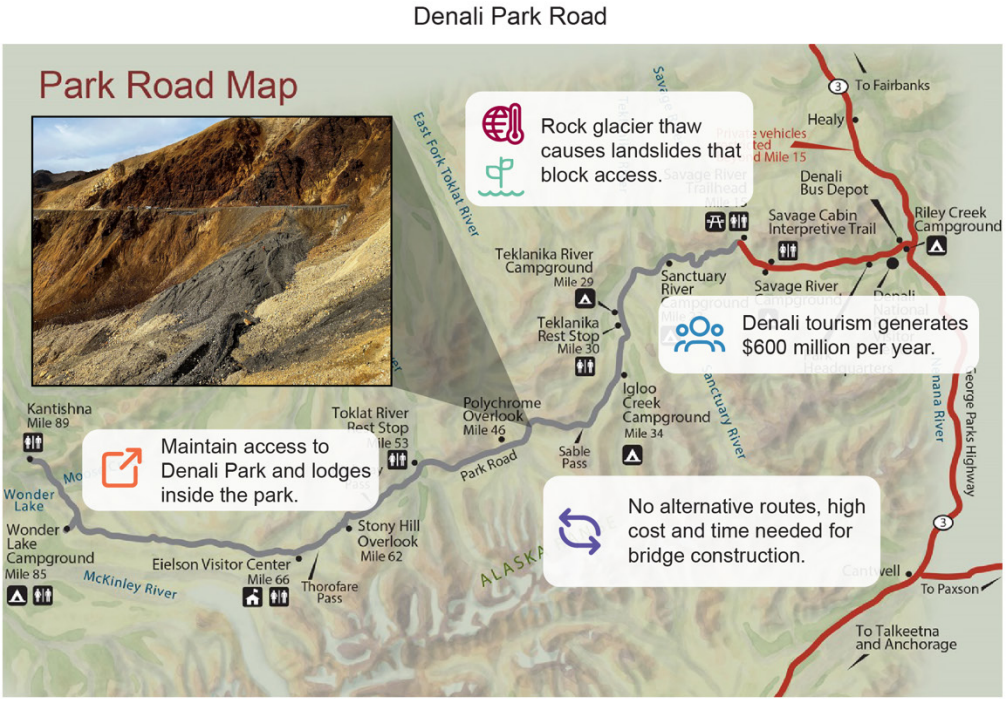
(SSP2-4.5) and 35.8% by the end of the century under a very high scenario (SSP5-8.5), for 2081–2100 relative to 1981–2010.[41,42]

Some of the most direct impacts of rising temperatures are on the cryosphere—snow, ice, and permafrost (KM 3.4),[45] with substantial, consequential impacts on hydrology, ecosystem function, infrastructure, and human health and livelihoods. Across the Arctic, temperature increases are driving a shortened snow cover season, melting glaciers, thawing permafrost, and less predictable sea ice extent (App. 4.3).[1,45] Snowfall has decreased in autumn and spring but increased in parts of Alaska in the midwinter snow season.[1] The Alaska snowfall season is projected to decrease across the state,[46,47] and water entrained in snowpack is projected to decrease between 20% and 60% by the 2050s (2040–2069, moderate emissions) and between 40% and 90% by the 2080s (2070–2099, higher emissions) in most of the southern and western parts of the state. The highest elevations and coldest parts of Alaska, however, could see no net loss or even increases up to 35% (such as in the Brooks Range) in snowfall during the midwinter snow season.[46] For March, historically the month of maximum sea ice extent, the Bering Sea ice extent has decreased by about 20,000 square miles per decade since 1957,[1] and record minimums in 2018 and 2019 were associated with warm ocean temperatures.[48] For September, historically the month of minimum sea ice extent, the Chukchi and Beaufort ice extents have decreased by about 27,000 square miles per decade and 31,000 square miles per decade, respectively.[1] These sea ice losses accelerated in the mid-1990s. Permafrost degradation and thaw described in previous NCAs continues and may be accelerating due to recent warm winters and, for 2018, increased snow cover (e.g., Douglas et al. 2021[49]), which insulates the surface from cold air above.[50] Previously reported projections of permafrost degradation may underestimate permafrost thaw rates.[51]

These extensive changes affect Alaska's society in many ways—in the context of Alaska's existing geography, governance, economics, demographics, cultures, and social services (Figure 29.2 provides two examples). By disrupting familiar patterns and conditions, climate change exacerbates existing tensions and conflicts across the state. As coastlines and riverbanks erode, and as fish and wildlife distributions shift, potential responses include relocating communities or using new areas for hunting, fishing, and other uses. However, current societal systems can constrain the options available for responding to change (KM 20.2). Land and resource management policies and practices, for example, may prevent or restrict the movements of people and their activities.[52] At the same time, the strong ties that Alaska Native Peoples have to their lands and waters are a vital consideration in any equitable responses to change.

## The Context of Climate Change Response




**The response to climate change depends on the desired societal outcome and is shaped by existing societal and environmental conditions.**

**Figure 29.2.** Two examples illustrate the interactions between climate change and societal and environmental factors for an activity important throughout much of the state and for a place that attracts many residents and visitors alike. Successful salmon fishing in rural Alaska villages is threatened by ecological changes affecting salmon spawning and survival (top; Boxes 29.3, 29.5). The $600 million annual tourism economy of Denali National Park is threatened by a thawing rock glacier that has damaged the access road (bottom; Box 29.4). Figure credit: (top) Ocean Conservancy; (bottom) adapted from NPS. Photo credit: NPS

Although Alaskans cannot stop global warming alone, they can choose to take actions that contribute to global efforts to limit climate change and be leaders in effective planning and adaptation (KM 31.3). From Alaska Native culture camps teaching climate and cultural resilience to courses on residential solar installation for homeowners and workers, Alaskans working together can accomplish a great deal. The effectiveness of cooperation, together with careful preparation and planning, was seen in the rapid and effective response to the November 2018 earthquake in Southcentral Alaska.[53] If Alaska's response to climate change remains fragmented, climate change will be intertwined with nearly all of the other persistent problems facing Alaska. If Alaska's society pulls together, much can be done to create lasting benefits for today and for future generations, contributing to a prosperous and just society in the state (Table 29.1).

**Table 29.1. The Intersection of Climate Change and Societal Context**

Climate change exacerbates existing societal tensions, but responding effectively to climate change can yield many societal benefits, as shown in the examples here for each of the chapter's Key Messages.

| Key Message | Examples of Challenges That Intersect with Climate Change | Examples of Opportunities for Climate Responses with Multiple Benefits |
|---|---|---|
| 29.1 Our Health and Healthcare Are at Risk | Inequitable access to basic nutrition and physical and mental healthcare services | Strong public health services |
| 29.2 Our Communities Are Navigating Compounding Stressors | Food insecurity | Increasing community capacity and agency |
| 29.3 Our Livelihoods Are Vulnerable Without Diversification | High prices and scarce jobs, especially in rural Alaska | Renewable energy and value-added industries |
| 29.4 Our Built Environment Will Become More Costly | High needs, high costs, and barriers to implementation | Cross-community learning, priority setting by communities themselves |
| 29.5 Our Natural Environment Is Transforming Rapidly | Allocation conflicts and cumulative effects of human activities | Ecosystem-based management and equitable participation |
| 29.6 Our Security Faces Greater Threats | Conflict at many scales and competition for limited resources | Recognizing and supporting widespread contributions to security |
| 29.7 Our Just and Prosperous Future Starts with Adaptation | The societal needs listed above present challenges to climate change adaptation | Cross-scale learning and cooperation to improve justice and equity |

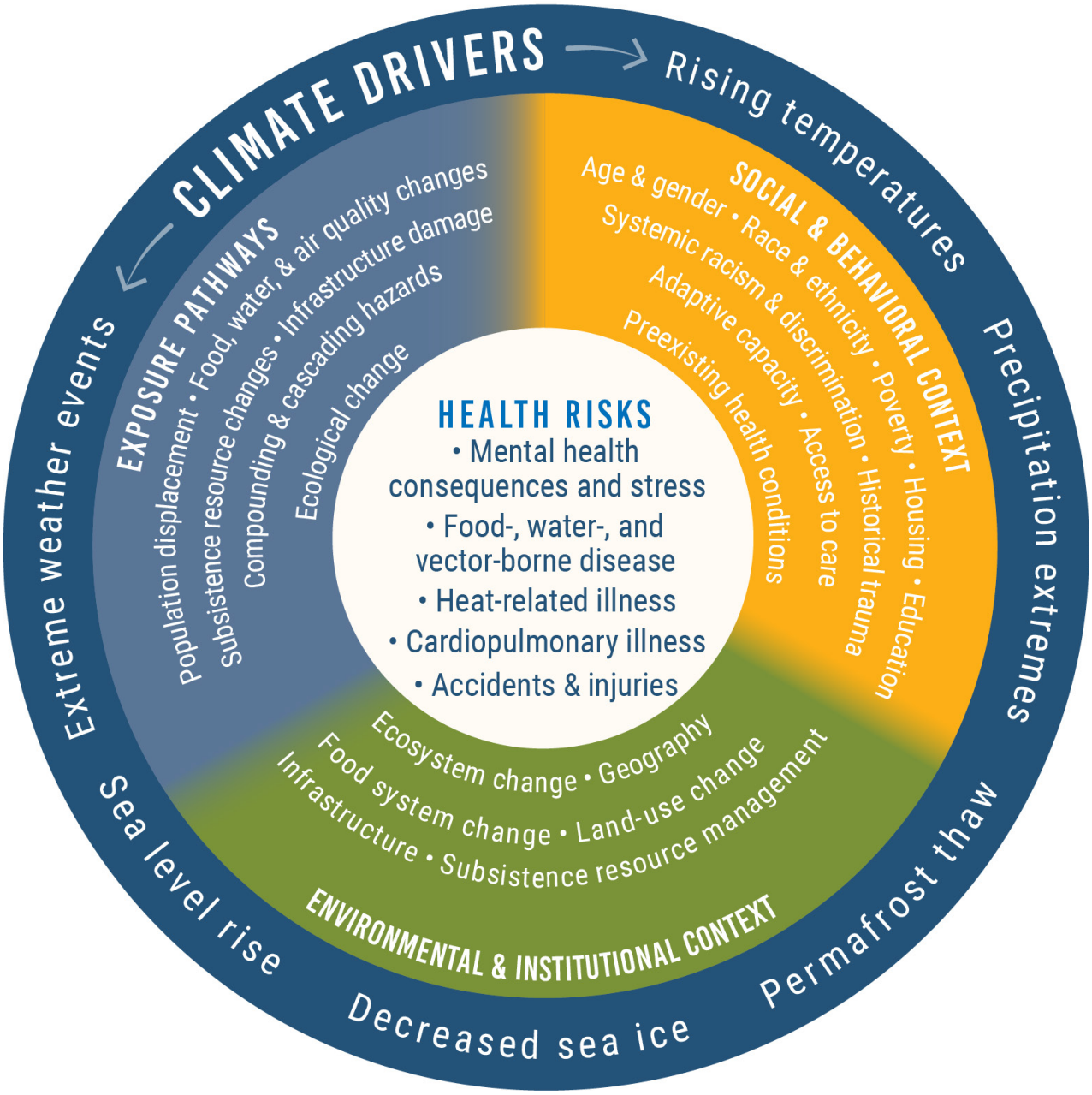
## Key Message 29.1

## Our Health and Healthcare Are at Risk

Health disparities in Alaska, including access to healthcare and health outcomes, are exacerbated by climate change (*high confidence*). The well-being of Alaska residents will be further challenged by climate-driven threats and by emerging diseases (*medium confidence*). Improving health surveillance and healthcare access statewide can increase resilience to events that threaten public health (*medium confidence*).

Many Alaskans, particularly Alaska Native Peoples, have a distinct connection to and understanding of the natural environment (KM 29.5) and depend on the land, sea, and natural resources for their economic activities, food security, health, culture, and overall well-being. This close connection to local ecosystems, combined with the geographical isolation of many communities and their resulting distance from healthcare and other services, creates a population particularly vulnerable to health impacts from the local effects of a changing climate (Figure 29.3) yet also fosters self-reliance and resilience.

## Climate, Health, and Well-Being in Communities




**The impacts of climate change on health and well-being depend on many social and environmental factors.**

**Figure 29.3.** Well-being includes physical, mental, and spiritual health outcomes, all of which are shaped by many contextual factors, including environmental change and governance, social and behavioral characteristics and systems, and the exposure pathways that connect the changing environment to human health. All of these contextual factors are affected by climate change and occur simultaneously. Adapted from Balbus et al. 2016.[54]

Climate change in Alaska highlights existing inequities confronting many racial and ethnic groups, including discrimination, lack of access to healthcare, lack of indoor plumbing, and poverty.[55,56,57] In rural Alaska especially, underserved communities often face food and water insecurity, inadequate sanitation, overcrowding in homes, limited transportation options, limited medical access, and significant geographical isolation.[58,59,60] People living in such settings are disproportionately impacted by climate change (KMs 15.2, 20.1),[61] and have limited options to respond to additional disturbances.

The lack of basic household sanitation facilities (Figure 4.16) contributes to health disparities, especially in rural Alaska. The lack of indoor plumbing was a key factor contributing to the high incidence of COVID-19 cases among Tribal communities (Focus on COVID-19 and Climate Change).[62,63,64] More than 3,300 households in more than 30 Alaska communities lack in-home piped water and sewer services.[65,66] In Alaska, the lack of water and sewer services is associated with multiple adverse health outcomes.[67,68,69] Environmental factors such as permafrost thaw, river erosion, and flooding exacerbate inequitable health-related infrastructure, and climate change has created new challenges to building and supporting sanitation systems. The Portable Arctic Sanitation System, developed by the Alaska Native Tribal Health Consortium and tested in five communities to date, provides households with treated water for drinking and a handwashing sink, in addition to a waterless toilet system. These systems allow households to meet basic water and sanitation needs in situations such as damage to existing water and sewer infrastructure or community relocation.[66] While not a replacement for a piped water system, these systems are a successful example of responding to climate hazards in Alaska (KM 16.3).

Climate change in Alaska is related to a range of environmental catastrophes, which can directly impact health in significant ways that may not be well known (KM 15.1). Flooding, for example, negatively impacts physical and mental well-being, with special and persistent implications for certain populations, such as pregnant people and children.[70,71] In Alaska, these effects are compounded by preexisting disparities, such as limited access to healthcare (e.g., pregnant people in rural Alaska typically travel to urban areas for childbirth) and the lack of alternative housing options. In the aftermath of ex-Typhoon Merbok in September 2022, which resulted in widespread flooding of a thousand miles of Alaska's coastline, people experienced loss of air travel service, multiday power outages, and damaged housing (often resulting in a subsequent need to move to a different community).[72]

Environmental disruption due to climate change can lead to increased rates of suicidality, among other negative mental health effects (KM 15.1).[73] These effects, including a profound loss of connection to a landscape altered by climate change, can increase instances of mental illness and spiritual grief in affected populations and subsequent generations.[74,75,76] Forced displacement inland due to rising sea levels, coastal erosion, flooding, and permafrost thaw disrupt social networks and increase instances of homelessness.[77,78,79] Alaska Native populations already experience significantly elevated rates of suicide, especially among youth.[80] Based on research with Inuit in Labrador, Canada, Alaska Native populations whose ways of life and culture depend on subsistence activities may be particularly vulnerable to negative mental health impacts related to climate change because of their deep connection to the land, exacerbated by existing disparities in mental health services (KM 16.1).[81]

Various health concerns connected to climate change have been raised by Alaska residents and public health officials (KM 15.1). For example, wildfire smoke exposure is associated with an increased risk of adverse health outcomes among Alaska Natives and rural residents.[82] This increased risk is thought to be due, in part, to underlying differences in rates of chronic disease, as well as access to healthcare and resources for exposure reduction (e.g., air filters).[82] Common exposure-reduction strategies may not be an option for many households. For example, few homes in Alaska have air-conditioning. During a wildfire smoke event that occurs at the same time as a heatwave, people must weigh the risks of opening a window to decrease the heat versus keeping windows closed to minimize smoke exposure. When developing adaptation strategies for climate hazards, it is critical to consider existing health disparities within communities, the relative capacity of individuals to adapt, and the potential to exacerbate existing inequities (KMs 15.3, 20.3).

The expanding geographic ranges of tick species and the potential implications for human health are another concern (KM 8.2). The blacklegged tick and western blacklegged tick, carriers of the bacteria that cause Lyme disease, are not established in Alaska, although the western blacklegged tick has been found on humans and domestic animals that have not reported recent travel out of the state.[83,84] Current conditions in

Southeast Alaska and some portions of Southcentral Alaska are suitable for the establishment of the western blacklegged tick, and models predict an increase in the suitability of tick habitat in many areas.[84] While there have been no known locally acquired human cases of Lyme disease in Alaska, the risk of occurrence is expected to increase, especially for those who spend a lot of time outdoors.[57]

Rabies is another disease that can be transmitted from animals to people, with potential connections to changing climate conditions due to shifting ranges of host species. In Alaska, rabies is found in populations of Arctic and red fox populations along the northern and western coasts. During the 2020/21 winter, there was a widespread outbreak of rabies in western Alaska, with more than 35 confirmed cases in animals, compared with an average of four to five cases each year. Changes in sea ice and prey availability may have played a role by increasing exposure of red foxes to rabid Arctic foxes and thus spreading rabies to inland areas as well as along the coast.[85,86]

Climate change is also affecting the ability to dry and store food in traditional ways[87] and increasing the potential for adverse health effects from processing and consuming fish and wildlife.[57] Wetter weather inhibits drying of fish and meat, and permafrost thaw and flooding damage ice cellars.[88] Additionally, human, marine mammal, and seabird health are increasingly threatened by harmful algal blooms (HABs), which produce a toxin that can cause severe illness or death when consumed (KM 10.1).[89,90,91,92] The largest bed of resting cysts of HAB species in the world has been discovered in the Chukchi Sea.[4] Warming ocean temperatures make these cysts more apt to hatch into massive and recurring toxic blooms.[4]

In general, there are limited conventional disease surveillance systems in Alaska for identifying, detecting, and monitoring climate-related hazards and conditions, as well as limited information on broader health impacts, such as the degree to which climate-related factors have impacted mental health. The development and sustainability of robust surveillance systems is hampered by many factors, including the state's small population and large geographic scale, limited in-state locations with adequate laboratory and diagnostic testing, and other healthcare limitations, such as access to healthcare and disconnected health databases. To fill these gaps, several local and Tribal programs have been implemented, such the Local Environmental Observer Network, Southeast Alaska Tribal Ocean Research, and Indigenous Sentinels Network, which facilitate integration of community observations.

In addition to limited health surveillance systems for climate-related risks, there are also large disparities in healthcare access and services in Alaska. The COVID-19 pandemic highlighted some of these gaps,[93,94] although some responses to the pandemic created or strengthened health partnerships and surveillance, which may support longer-term action to improve healthcare and health outcomes around the state. Because more immediate crises, such as a disease outbreak, can reduce the capacity for responding to longer-term healthcare challenges, such as those posed by climate change, continued investment in these types of improvements in the healthcare system statewide may increase resilience to climate-driven health impacts.

## Box 29.1. "I've Been Called to Pray"

Tragedies related to climate change, such as deaths associated with changing ice conditions, impact more than just those who are directly affected. Alaska Native communities, although often geographically spread out, remain intimately connected via cultural and family ties, social media, and other networks, such as churches (KM 16.2).

Iñupiaq Elder Gladys I'yiiqpak Pungowiyi, of Kotzebue, a predominantly Inupiaq town in northwestern Alaska, states:

> *I've been called to pray.*
>
> *On Facebook, there are mothers, grandmothers requesting prayer for their lost loved ones who fall through the ice and their families who are going through a hard time. Especially when they're not found.*
>
> *I've been called to pray for people that are affected mentally. What's happened over the years is that a number of skilled hunters were lost when they went out hunting. Either they fall through the ice or just disappear. It seems like every springtime people start saying "Our men are going out hunting. Please pray for them." It's hard.*[95]

### Gladys I'yiiqpak Pungowiyi

**Strong connections between individuals and communities are vital in rural Alaska.**

**Figure 29.4.** Iñupiaq Elder Gladys I'yiiqpak Pungowiyi is shown here using a laptop computer in Kotzebue, Alaska, August 19, 2022. Photo credit: ©Cana Uluaq Itchuaqiyaq.

## Key Message 29.2

## Our Communities Are Navigating Compounding Stressors

Climate change amplifies the social and economic challenges facing Alaska communities (*high confidence*). Resource shifts, coastal and riverbank erosion, and disproportionate access to services will continue to threaten the physical and social integrity of these communities (*high confidence*). Increased adaptation capacity and equitable support have the potential to help rural and urban communities address Alaska's regionally varied climate-driven threats (*high confidence*).

Climate change affects all Alaska communities but in regionally distinct ways for urban areas compared with rural, predominantly Alaska Native, places. Lacking road connections, Alaska's rural areas are more remote than rural areas in the Lower 48. About 79% of Alaskans live in urban areas.[96] This concentration creates challenges for the development and maintenance of infrastructure in rural areas where economies of scale do not exist (KM 12.2). For example, there are large disparities in exposure to the effects of climate change and inequities in access to resources and capacity for responding to those effects.[97]

The limited reach of broadband internet access in the state is testament to this challenge.[98] As of 2023, 46% of Alaska communities remain unserved according to the National Telecommunications and Information Administration's minimum broadband standards.[99] An additional 3% are considered "underserved," lacking internet that meets the new baseline for functional service. Many fewer communities have access to affordable internet, with some paying as much as $500 per month with usage caps. Lack of broadband and cell reception diminishes access to healthcare (via telemedicine), educational opportunities, emergency response capability, and resilience to shocks from environmental hazards and extreme weather events,[100] which are expected to increase with climate change.

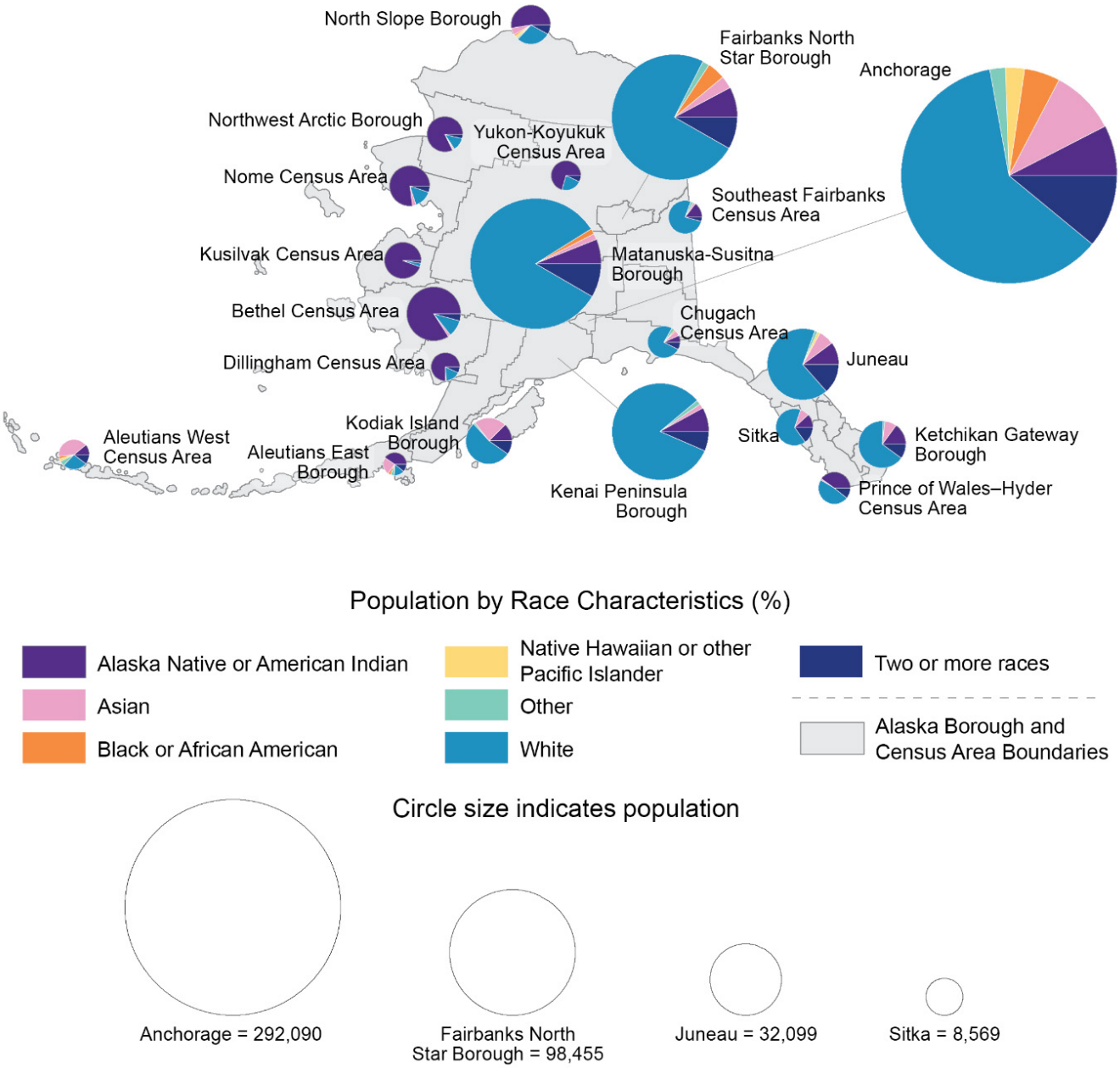
As another example, the frequency of wildfire seasons in which more than 1 million acres are burned is increasing throughout much of western and Interior Alaska (KM 7.1; Focus on Western Wildfires). In addition to health concerns (KMs 14.2, 29.1), smoke can limit visibility and interfere with air travel. This disproportionately affects rural areas accessible only by plane, leaving Alaska Native Elders, other older adults, and those with existing respiratory ailments without a means to escape environmental stressors.[34]

Both urban and rural communities face significant infrastructure and access challenges related to permafrost thaw and erosion (KM 29.4). Rural communities facing relocation are among the hardest hit, as are low-income populations in urban areas. In the Fairbanks North Star Borough (FNSB), a comparison shows that the average value of residential land[101] with shallow permafrost soil[102] is about 40% the average value of residential land borough-wide. Low-income populations in FNSB disproportionately reside in homes on or near permafrost-affected soils and are thus disproportionately impacted by damage resulting from permafrost thaw.

Alaska's population is gradually becoming more diverse (Figure 29.5). The percentage of White residents dropped 2% from 2010 to 2020.[103] The Alaska Native population increased nearly 10%, and the Black population increased 2%, but the largest growth was among residents with Asian heritage, whose population increased 32%. Much of the non-White population growth occurred in urban areas where, as in other parts of the United States, BIPOC (Black, Indigenous, and People of Color) populations historically were subject to discrimination and exclusionary housing practices. Such discrimination continues to shape the character of Alaska's urban neighborhoods today.[104] More research could illuminate the disproportionate impacts of climate change experienced by BIPOC communities in urban Alaska, which, if consistent with national

trends, are expected to be substantial. Increased knowledge of the current and historic inequities in relation to climate change and other environmental factors would help inform adaptation and mitigation measures that protect and uplift vulnerable populations.

## Racial and Geographic Distribution of Alaska's Population




**The racial makeup and population density of Alaska's communities vary greatly by region, creating the potential for varied exposures and disparate impacts across subpopulations**

**Figure 29.5.** The total Alaska population estimate in 2021 was 734,323.[105] Urban areas account for the majority of Alaska's population. Racial and ethnic characteristics throughout the state vary greatly by region, as do the impacts of climate change. Alaska's urban areas are particularly diverse, and given a legacy of historic discrimination, there is still much to learn about the unique ways racial and ethnic subpopulations are impacted by climate change in Alaska and how these vary around the state. Circle sizes are proportional to population for each region. Figure credit: Northern Social-Environmental Research, Ocean Conservancy, and University of Alaska Fairbanks.

Food security is a major priority for the state of Alaska (Box 11.2).[106] Food prices may be more than twice as high in rural versus urban communities, with considerably less variety.[107] Alaska Supplemental Nutrition Assistance Program (SNAP) recipients receive the third-highest benefit per person in the United States, behind only Hawai'i and Guam. The number of households receiving SNAP benefits in Alaska increased 8% between 2019 and 2020.[108] The vast majority of food Alaskans purchase is grown elsewhere, arriving via long supply chains (Focus on Supply Chains). COVID-19 highlighted the fragility of the state's food supply and serves as an analog for the potential impacts of climate-related environmental shocks. During the pandemic, backlogged ports and restrictions on overland trucking through Canada made food and other essentials difficult to obtain. Remote regions of Alaska were among the hardest hit by supply chain disruptions after a primary air carrier in rural Alaska declared bankruptcy in April 2020 (Focus on COVID-19 and Climate Change). This left many rural off-road-system communities without a commercial airline to deliver mail and freight, including medications and food supplies.

Given the high cost of food and the vulnerability of rural transportation networks, subsistence activities (including hunting, fishing, and sharing) are critical in rural Alaska. This is especially true for Alaska Native communities, as well as for many non-Native and urban residents. About 45.4 million pounds of wild food were harvested in Alaska statewide in 2017, with an estimated replacement value of $262–$523 million (in 2022 dollars),[109] not counting their cultural and spiritual value. Yet the success of subsistence harvests is influenced by numerous external and climate-driven factors. These include shifting distribution, abundance, and migratory patterns of fish, birds, and mammals that affect availability to hunters and fishers; rising fuel costs that increase the cost of hunting, fishing, and gathering activities; and changing weather, flooding, and dangerous ice that increase risks to those engaged in these practices (KMs 8.1, 29.3).[87,109]

Climate change will have some positive impacts on Alaska food security, particularly in the agricultural sector. A longer growing season, increased number of growing degree days, and increased yields are expected to enhance the share of locally grown foods consumed by Alaskans.[110,111,112] On the other hand, pests, flooding, and ground collapse resulting from permafrost thaw will pose challenges.

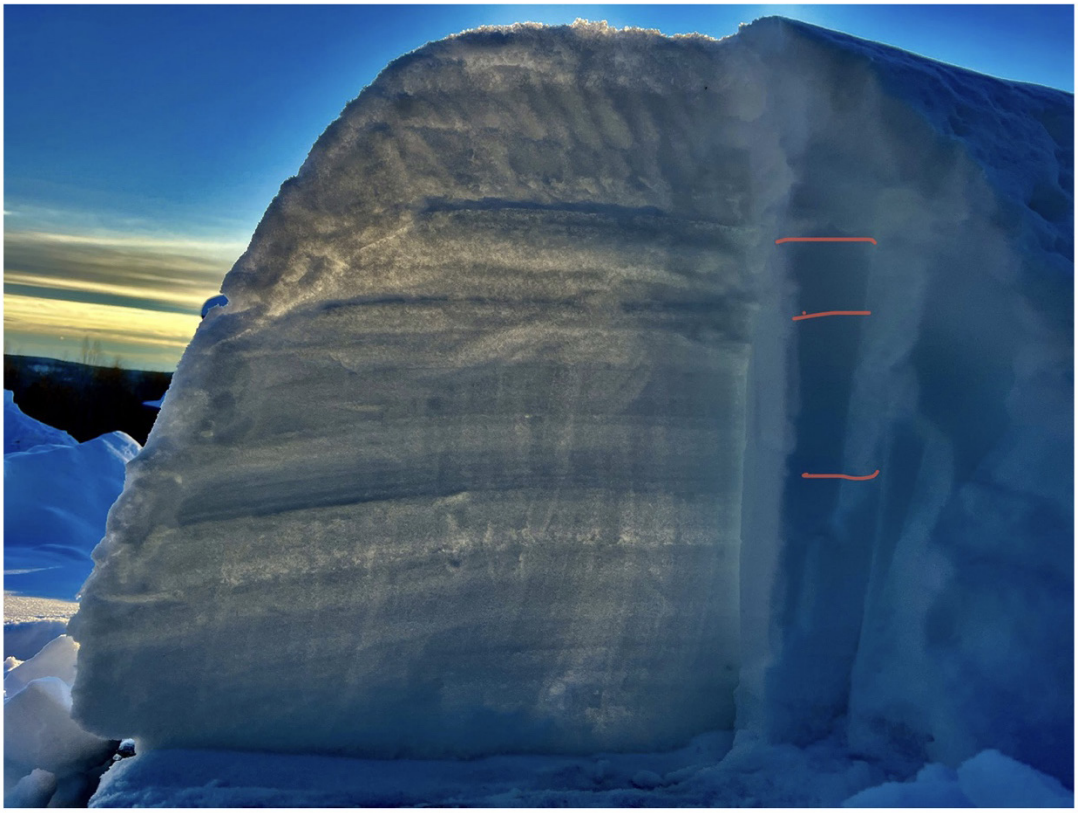
## Box 29.2. "We Had to Dig In and Out of Our House"

Snow and cold are expected in Fairbanks and Interior Alaska in winter. Rain is not. More than an inch of rain fell on top of feet of snow during the 2021 holidays. The resulting ice made roads impassable, caused power outages, delayed emergency services, damaged homes, and was linked to at least one highway fatality months later as roads remained dangerously icy into spring.[113,114] State and federal disaster declarations were issued as well.[115,116] More extreme weather events are expected in a warming Alaska.

Fairbanks resident and tax preparer Marjorie Casort recalls, "I shoveled my driveway seven times in five days. In April we are still feeling the effects, with an inch of ice stubbornly clinging to roads. Many of my elderly clients are housebound, unable to even cross the road to check their mailbox because of the dangerous ice conditions".[117]

Social relationships are an essential component of resilience. Denali resident Erica Watson explained, "I trust my friends and neighbors to know what they need to do to stay warm, to check in on each other, to care for each other's homes the way we would our own."[118]

### Cross-Section of Snowpack After the December 2021 Storm



**A rain-on-snow event in December 2021 blocked roads and caused other damages.**

**Figure 29.6.** Shown here is a 20-inch-high cross-section of the snowpack near Fairbanks, Alaska, taken on January 23, 2022. Red lines indicate ice layers from rain-on-snow events. The ice persisted through the winter, impeding travel for humans and moose. Photo credit: ©Bill Witte.

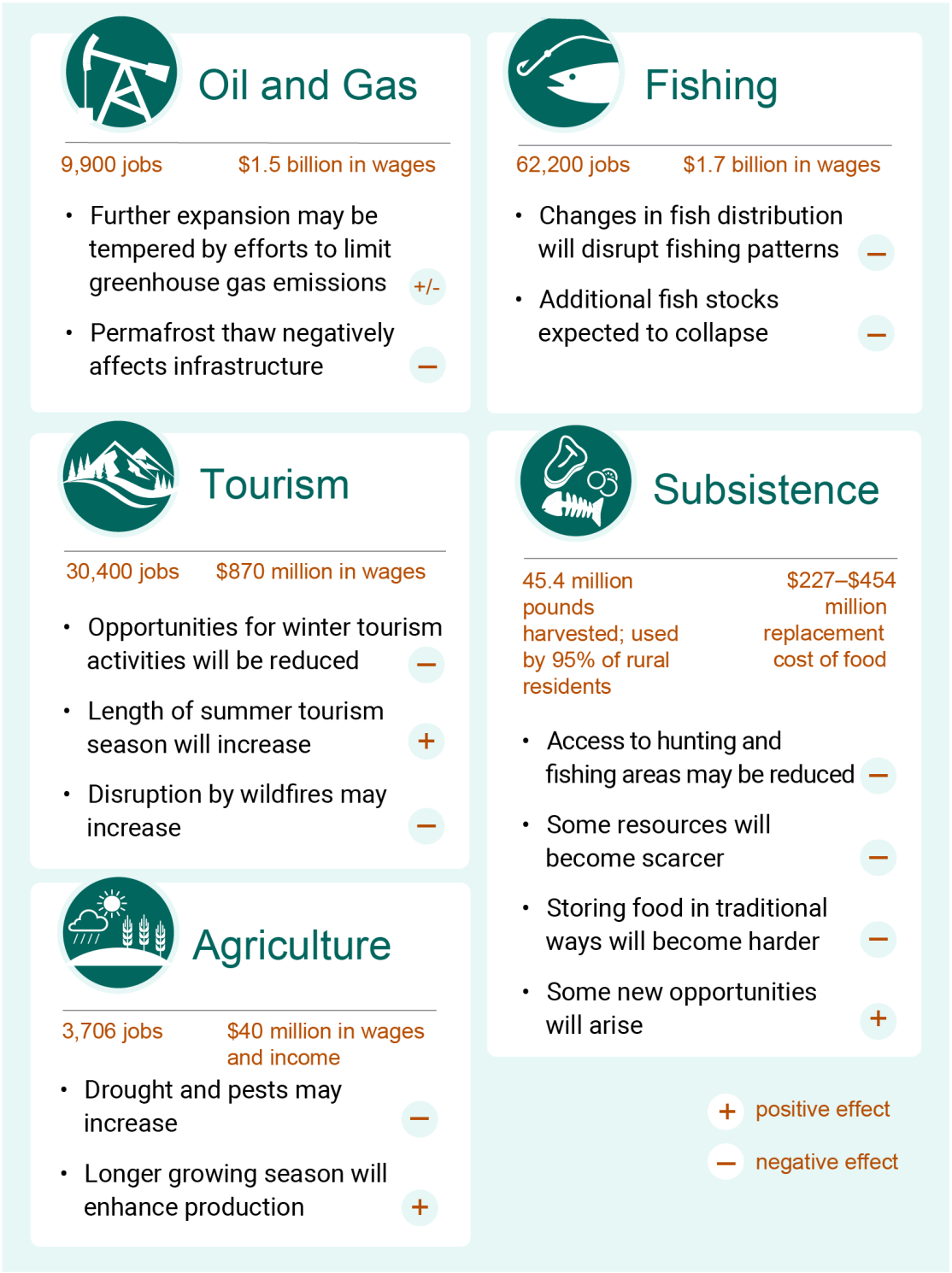
## Key Message 29.3

## Our Livelihoods Are Vulnerable Without Diversification

Livelihoods, especially those dependent on natural resources, are at risk around Alaska. While advancing climate change has contributed to the collapse of major fisheries and is undermining many existing jobs and ways of life (*high confidence*), it may also create some opportunities related to adaptation and response (*medium confidence*). Economic diversification, especially expansion of value-added industries, can help increase overall livelihood options (*medium confidence*).

Many jobs in Alaska are affected directly or indirectly by climate change—through alterations in abundance and distribution of fish species, through changes in access to lands and waters dominated by permafrost and ice, and through the cascading effects of a changing economy (Figure 29.7). Sustaining healthy livelihoods and ways of life in Alaska involves more than wages and salaries. Traditional cultural practices outside the cash economy include the harvest and sharing of fish, wildlife, and berries. Climate-driven changes to lands and waters, along with societal trends such as greater adoption of mainstream food practices, can reduce opportunities for subsistence harvests and thus affect cultural, nutritional, and spiritual well-being, especially for Alaska Native communities (KM 16.1).

## Climate-Sensitive Employment in Alaska




**Climate change is expected to have wide-ranging effects on key economic sectors in Alaska.**

**Figure 29.7.** The figure shows examples of key sectors of Alaska's economy that are expected to be affected in various ways by climate change. Many, but not all, of the changes are negative. Data sources: Oil and Gas;[96,119] Agriculture;[120] Tourism;[121] Fishing;[122] Subsistence.[87,109] Figure credit: Northern Social-Environmental Research, University of Alaska Fairbanks, and Ocean Conservancy.

Climate impacts have severe socioeconomic consequences for Indigenous Peoples, small rural communities, and industries throughout Alaska.[123,124,125,126] For example, the Yukon River king salmon subsistence fishery has been closed river-wide since 2020, with no expected opening date in the foreseeable future. This is the first occurrence of a year-round Yukon River subsistence king salmon closure. King salmon contribute 64% of all protein to rural Yukon River communities. A multiyear closure of the subsistence king salmon fishery due to climate change (Box 29.5) and the overharvesting of ocean king salmon via bycatch is disastrous to Indigenous Peoples' physical, mental, cultural, and spiritual well-being.

Alaska's commercial fisheries have also been impacted. Alaska's seafood industry generates $6.1 billion (in 2022 dollars) in economic outputs,[122] accounting for 60% of the volume and 31% of the value of the US fishery catch.[127] A number of fisheries have been closed or dramatically reduced due to fewer fish (KM 10.2).[128,129,130,131] In January 2022, the US Department of Commerce declared several fishery disasters because of the extreme economic impact of their decline.[132] Climate change has had a large role in these fishery disasters.[133]

Climate change has negatively impacted the condition, growth, survival, reproduction, population biomass, and harvest of marine fishes,[134,135,136] salmon,[29,126,137,138,139,140] and crab.[131,141] In addition, groundfish and crab distributions have shifted northward or offshore,[142,143] following colder water, and the timing of groundfish spawning[144] and salmon spawning migration[145] has been altered (KM 8.1). Salmon are in double jeopardy because climate affects both their freshwater and marine habitats (Box 29.5). Changes in spawn timing will require changes in survey timing and stock assessments.[146,147] Changes in fish and crab distribution will require adjusting survey locations and area-based management measures.[148,149] Fishers will need to adjust the timing of harvest or switch to other harvest targets.[150] Local economies can be resilient through income diversification such as participating in several different fisheries.[151] Proactive adaptive management can help in the face of rapid climate change. One recent example is the management of Prince William Sound pink salmon during the extreme 2019 drought. After detecting high mortality early in the fishing season, managers limited harvest at critical times so that fish could successfully migrate and spawn.[23]

Warmer temperatures and changes in precipitation patterns also affect the distribution of and access to terrestrial and marine mammals (KM 8.3).[152,153] Increasingly volatile storms and changing ice and water levels are of immediate concern because they threaten the availability of wild foods, as well as safe access to these subsistence resources by boat, snowmobile, or all-terrain vehicle.[153,154] Shorter durations of suitable conditions for spring marine mammal subsistence hunting in the Arctic due to loss of sea ice will require adaptation of traditional hunting practices.[155] On land, more frequent rain-on-snow events can increase stress and mortality for wildlife,[156] reducing availability. Migratory patterns for caribou and other species are also changing,[157] again affecting access for hunters.

Berries are of high nutritional and cultural importance to Indigenous and rural communities.[158] A recent survey indicated that, statewide, berry harvests have become less reliable due to declining abundance or increased variability.[159] Changes in precipitation and temperature are expected to continue to affect berry production,[160] and they may also impact pollinators.[159]

The intersecting demands of the climate crisis and the high cost of living in Alaska have forced Alaskans to creatively address interrelated challenges related to energy and heat, crisis response, and food equity and access (KM 19.3). Union electricians and laborers, private contractors and installers, and utility inspectors are training a growing workforce in clean energy industries.[161,162] Farmers and artisans are providing local goods, training aspiring agriculturalists, and creating new employment opportunities in mariculture.[163,164] In Fairbanks, community members are working with local healthcare providers to create crisis response teams and centers that focus on harm reduction and community care, needs made greater by climate change.[165]

## Box 29.3. What It Means to Lose Salmon

Prior to the recent period of unusually warm water temperatures in the Gulf of Alaska, the Chignik fishery typically supported returns of more than one million sockeye worth nearly $10.2 million (in 2022 dollars) a year to the fishermen. In 2021, in part due to the effects of ocean warming, returns were so poor that some residents chose not to subsistence fish out of fear of harming the fragile run.[166] Resident George Anderson explained how that felt: "We had something that we took for granted—that the fish were just always going to be there for smoking, salting, freezer, whatever. And to have that not be there for you is just something we were never prepared for."[166]

Some nonprofit and industry organizations have tried to help by donating fish. But for the predominantly Alutiiq community, subsistence is not just about food, it is also a connection to place and family.

"It's our lifeblood. Chignik's going to go away if we can't get this run back up to where it used to be," said Al Anderson, another Chignik fisherman.[166]

### Unloading Salmon Sent to Chignik in Response to the Fishery Disaster

**Donations of salmon provided much-needed food to Chignik and other small communities.**

**Figure 29.8.** Boxes of salmon are unloaded from a small plane in response to the fishery disaster in Chignik, Alaska, July 11, 2022. Photo credit: ©Miranda Lind.

## Key Message 29.4

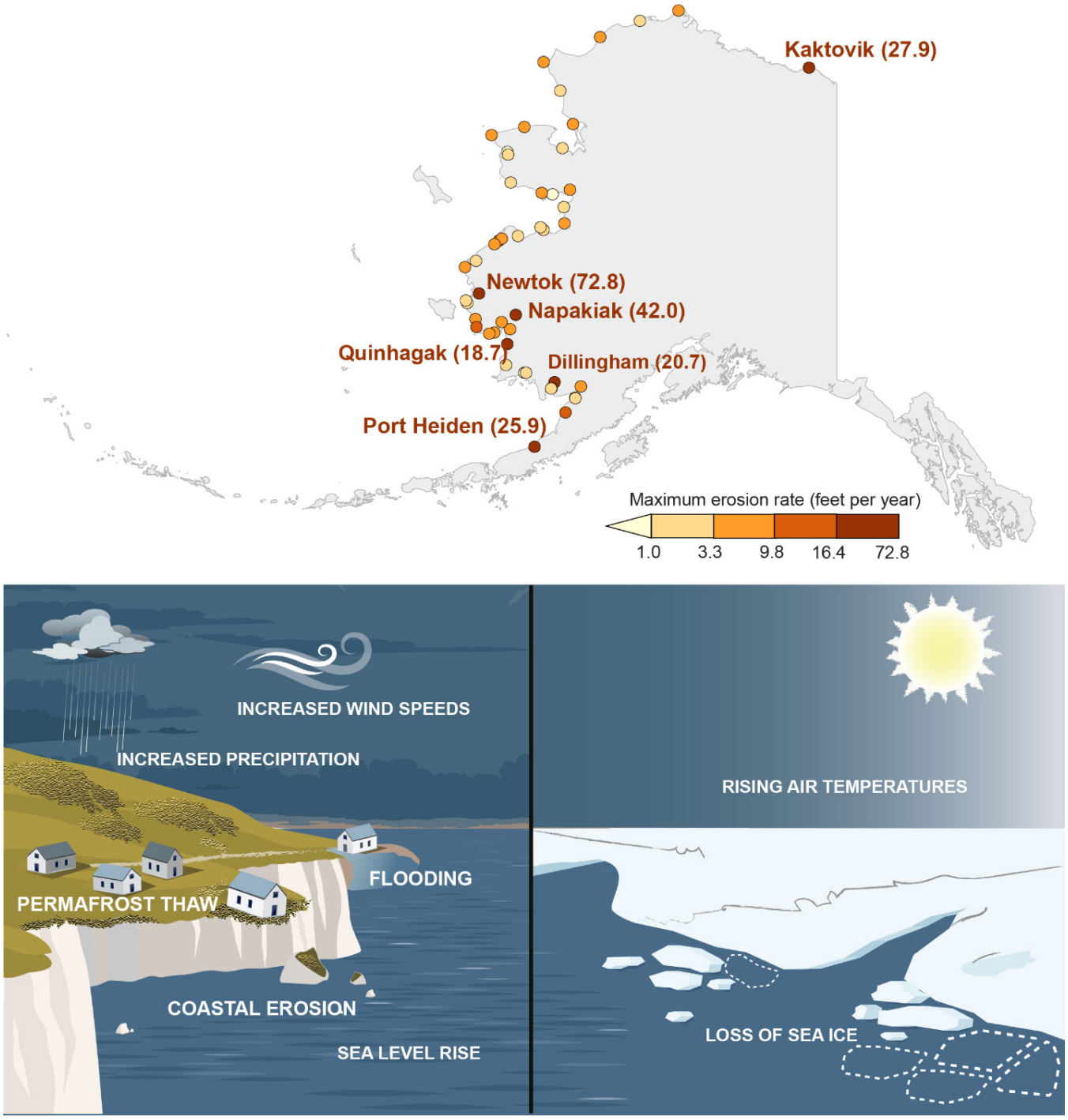
## Our Built Environment Will Become More Costly

Much of Alaska's infrastructure was built for a stable climate, and changes in permafrost, ocean conditions, sea ice, air temperature, and precipitation patterns place that infrastructure at risk (*high confidence*). Further warming is expected to lead to greater needs and costs for maintenance or replacement of buildings, roads, airports, and other facilities (*high confidence*). Planning for further change and greater attention to climate trends and changes in extremes can help improve infrastructure resilience around Alaska (*high confidence*).

Power, water, and transportation infrastructure in Alaska varies from large-scale and modern in urban areas to small-scale and even rudimentary in some villages. Air transport depends on suitable weather for flying and adequate runways in the destination community. Transport by water, delivering fuel and other heavy goods to many communities, requires rivers or coastal waters deep enough for barges and adequate offloading sites or facilities. Most communities lack backup systems for water, sewer, and electricity, leaving them vulnerable to disruption. Emergency housing may be limited to the school gymnasium as the largest indoor space in the community. Many Alaskans, especially in rural areas, also depend on remote camps for hunting and fishing to produce food. These camps are vulnerable to climate-driven damage and disruption.

Buildings and other infrastructure throughout Alaska are at risk from flooding, erosion, and permafrost degradation (Table 13.1; Figure 29.9).[167,168,169,170] More than half of Alaska's communities are at the highest threatened level according to the most recent statewide report.[171] For example, on Alaska's northern and western coastlines, communities face between 1 and 72.8 feet of erosion per year (KM 9.2).[172,173] Recent progress has been made to understand local flood and erosion vulnerability for Alaska communities by determining erosion rates [173] and historical flood heights (Figure 29.15); however, these reports are not available for all communities. Given that 80% of Alaska is underlain by permafrost (Figure 8.5),[174,175] regional infrastructure damages are projected to be high.[176] Modeling erosion's dependence on permafrost integrity and persistence has been an emphasis of recent research.[177] However, the widespread lack of permafrost presence assessments, and the degree to which local erosion depends on permafrost responses, is a key source of uncertainty in forecasts for specific Alaska communities.[178] Extensive coastal and riverbank erosion has also exposed old gravesites in western Alaska,[179,180] and permafrost is integral for cold storage in many Alaska Native communities and camps.

## Coastal Erosion Rates and Processes in Alaska




**Coastal erosion is a major threat around Alaska.**

**Figure 29.9.** The figure shows rates of coastal erosion in selected communities (**top**) and coastal erosion processes in Alaska (**bottom**). Data are unavailable for many parts of Alaska's extensive coastline, but erosion risk is high in much of the state (Figure 29.14). Coastal erosion processes are affected by many aspects of climate change (bottom), exacerbating the problem. (top) Adapted with permission from Overbeck et al. 2020;[173] (bottom) adapted with permission from the University of Alaska Fairbanks, Alaska Arctic Observatory and Knowledge Hub.

Alaska Native communities face an estimated $4.8 billion (in 2022 dollars) in costs to infrastructure from environmental threats over the next 50 years.[181] These costs may be significantly underestimated due to limitations in current model-based approaches[182], as well as to the omission of dispersed but culturally vital infrastructure such as fish camps. Various assessments have been completed to try to determine the cost of environmental changes to communities.[178,181] The costs of responding to climate change are unevenly distributed, with rural areas facing greater costs and few benefits, in contrast to urban areas that will realize some benefits such as reduced heating expenses and where the costs of infrastructure maintenance will be spread over a much larger population base (KMs 11.3, 12.2).[97]

Communities dealing with flooding, erosion, and permafrost degradation are responding immediately as well as planning long-term adaptations, which generally include a combination of protection of infrastructure in place, raising buildings out of the floodplain or moving them out of vulnerable areas, and entire community relocation (which has been the case for Newtok moving to the new site of Metarvik) (KM 9.3; Figure 9.5).[183] As mentioned earlier, however, relocation options may be limited by the availability of land that is culturally, economically, politically, and environmentally suitable. An additional complication is that no single agency has financial responsibility for the costs of relocation.[52]

## Box 29.4. The Cost of Thawing Ground for Alaska Industries

The oil development and production industry on Alaska's North Slope also faces challenges from thawing permafrost. Intensive efforts are now required to keep the ground cold and solid to support roads, pipelines, and buildings (KM 5.3),[184,185] and these are short-term solutions. Thawing permafrost will drive up the costs of North Slope operations.[184] Similar problems are expected with infrastructure elsewhere in the state, potentially reducing the viability of some industries.

Thawing ground can damage infrastructure, affecting many economic sectors around Alaska. In 2021, a landslide from a thawing rock glacier in Denali National Park cut off a section of the 92-mile road that takes visitors deep into the park (Figure 29.2).[186,187] The rate of ground slumping and damage to the road had accelerated by summer 2022.[188] A bridge over the damaged section of the road is estimated by the National Park Service to cost $102 million (in 2022 dollars). Other sections of the road are also at risk. Access to the park, which generates some $680 million (in 2022 dollars) in tourist spending each year, will be hampered at least through the 2024 season.

### Pretty Rocks Landslide, Denali Park Road

**Thawing permafrost limited access to Denali National Park.**

**Figure 29.10.** A slump in the Denali Park Road at the Pretty Rocks location was caused by movement of the rock glacier beneath the road, September 16, 2021. Photo credit: NPS.

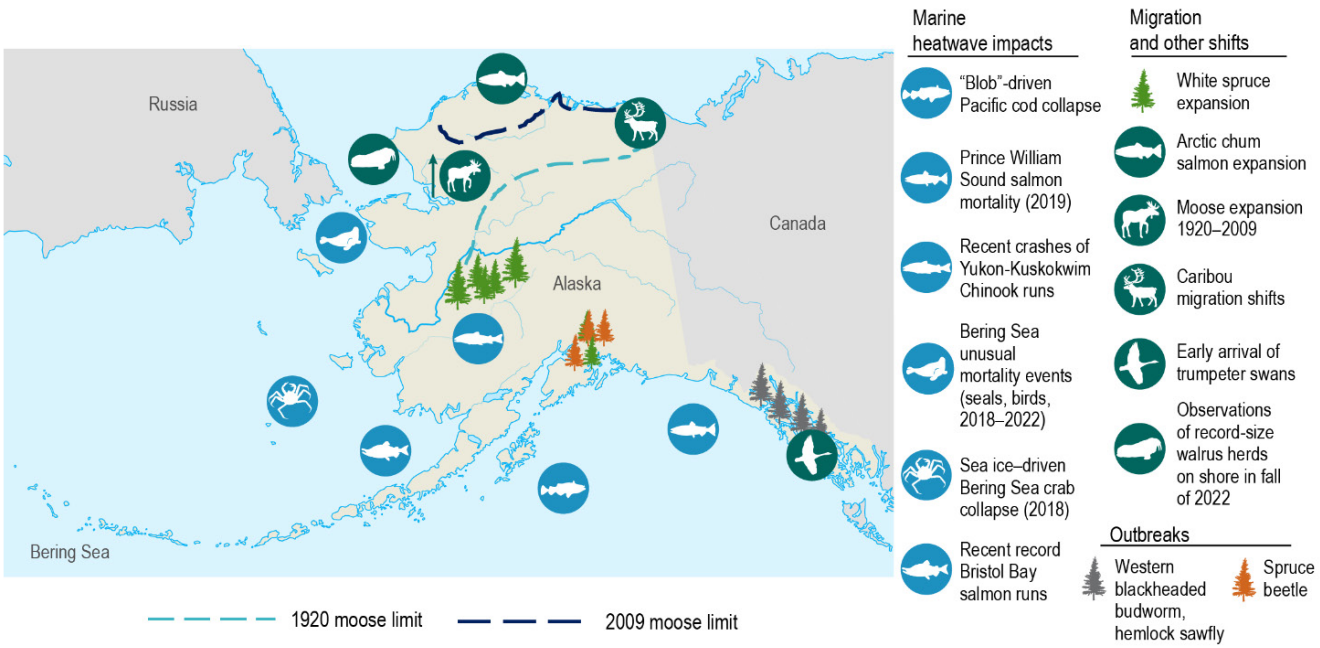
## Key Message 29.5

## Our Natural Environment Is Transforming Rapidly

Alaska's ecosystems are changing rapidly due to climate change (*high confidence*). Many of the ecosystem goods and services that Alaskans rely on are expected to be diminished by further change (*medium confidence*). Careful management of Alaska's natural resources to avoid additional stresses on fish, wildlife, and habitats can help avoid compounding effects on our ecosystems (*medium confidence*).

Alaska enjoys large, unfragmented marine and terrestrial ecosystems. This abundance makes possible hunting and fishing for subsistence use, cultural well-being, recreation, and commercial activities. At the same time, there are conflicts over land use and the allocation of hunting and fishing opportunities due to different land management regimes or distribution of harvest opportunities, with competing claims from traditional, commercial, and recreational constituencies.[189] Climate change is expected to exacerbate existing challenges by shifting the distribution and abundance of fish and wildlife and by increasing disturbance to lands and waters (Figure 29.11; KMs 8.1, 8.2). Climate-conscious management efforts can help individuals and communities adjust but cannot by themselves address the underlying changes that will continue to occur.

## Major Recent Ecological Changes




**Climate change has caused or contributed to extensive ecological effects throughout Alaska in recent years.**

**Figure 29.11.** Warming ocean waters, extreme heat events, and other changes, including the events shown in Figure 29.1, are affecting ecosystems across Alaska. Some species' ranges are expanding, including chum salmon in Arctic rivers,[190] moose[191], and beaver[192] in the Arctic (not shown), and white spruce in western Alaska (KM 8.2).[193] Migration timings or patterns are changing, for example trumpeter swans in Southeast Alaska[194] and caribou in the eastern Arctic. Marine heatwaves and reduced sea ice cover are affecting seabird, fish, and seal populations: the North Pacific "Blob" (Figure 29.1) contributed to Pacific cod collapse, the 2019 Southcentral heatwave affected Prince William Sound king salmon survival,[139] and low sea ice caused or contributed to the collapse of crab fisheries and unusual mortality events for seabirds and ice seals in the Bering Sea region (2018–2022) (KM 10.2; Figure 10.1). In 2022, Pacific walrus hauled out in record numbers in the Bering Strait area,[195] suggesting that the minimum population estimate may be higher than previously thought, even if the range may be shrinking. Insect distributions and outbreaks have also changed.[196,197] In Southeast Alaska, outbreaks of western blackheaded budworm and hemlock sawfly have damaged forests in the wake of the 2017–2019 drought.[198] The 2019 heatwave in Southcentral Alaska contributed to spruce beetle expansion in that region and extreme fire activity on the Kenai peninsula (KM 7.1; Box 7.1). Salmon runs responded variably: Yukon–Kuskokwim River king salmon runs have been decimated,[139] while Bristol Bay has had record sockeye salmon returns. Figure credit: USGS, NOAA Fisheries, and Ocean Conservancy.

Climate change has negatively impacted nearly all aspects of the life history of commercial groundfish, salmon, and crab (KMs 10.2, 29.3). Arctic seabirds and marine mammals have also experienced reproductive failure, unprecedented mortality, and changes in migratory behavior. Extreme ocean warming and record low sea ice in the Chukchi Sea are affecting the entire food web[199,200,201] and possibly transforming the ecosystem.[143,202] For example, the lowest abundance of marine zooplankton in a decade was observed in recent warm years (2017 and 2019), combined with a decline in large, fatty Arctic species of zooplankton and an increase in smaller, less calorie-dense sub-Arctic species.[203,204] In turn, fish such as Arctic cod and saffron cod, which feed on zooplankton, were not as robust.[205] Subsequently, seabirds and marine mammals preying on these less nutritious fish experienced increasingly frequent reproductive failures and mortality. Emaciated seabird carcasses were found on beaches during extreme mortality events in the Bering and Chukchi Seas,[201] and the body condition of ice seals has declined.[206] In addition, the ranges of ice-dependent species such as polar bears[207] and walrus[208] are shrinking.

Ocean acidification is harmful to some Arctic phytoplankton and zooplankton.[209,210] Laboratory studies have shown that the early life stages of commercial fishes such as northern rock sole,[211,212] walleye pollock, Pacific cod,[213,214,215] and salmon[140,216] are sensitive to more acidic waters and to resulting food web changes.[135,211] Laboratory experiments suggest that Alaska commercial crab species are also highly vulnerable.[141,217,218,219,220,221] Although no studies of the impacts of ocean acidification on crabs in Alaska have been conducted, a study of Dungeness crab off California showed that shell dissolution was observed in areas of high acidification, reducing growth.[210] Finally, seals, walrus, and marine birds may be affected by the vulnerability of their prey.[222]

Climate changes and extreme events are also contributing to terrestrial changes, affecting species distributions, habitats, resource availability, and human access (KMs 2.2, 29.4; Focus on Compound Events). Moose and beaver are colonizing previously inhospitable Arctic areas,[191,192] in part due to temperature-driven increases in shrubs, and there is evidence salmon are colonizing streams where they were previously rare or absent,[190] presumably due to warmer waters. Ongoing warming is also associated with rapid changes in vegetation. Alaska residents are also noting unusual plants.[223] Decreases in berry production have been noted by communities in Alaska, related to multiple climatic drivers (e.g., Herman-Mercer et al. 2020[160]). Exceptionally high midsummer tundra productivity ("greening") has been observed on the North Slope of Alaska, but lower productivity ("browning") has continued in Southwest Alaska due to drying.[224] In 2019, the rapid expansion of a spruce beetle outbreak in the Susitna Valley (ongoing since 2016) caused extensive spruce mortality over 1.6 million acres (Box 7.1),[198] due in part to warmer temperatures increasing beetle development rates. In Southeast Alaska, hemlock sawfly outbreaks caused defoliation and mortality on more than 500,000 acres of forest, and a developing western blackheaded budworm outbreak is affecting Sitka spruce.[198] Both are plausibly[225] related to the unprecedented 2017–2019 drought in the region.

Landscape changes due to fires, permafrost, and their effects on other processes are climatically driven and increasing. Projected fire-driven transitions from conifer- to deciduous-dominated boreal forest[226] appear to be manifesting at regional scales. Wildfires in 2019 (Southcentral Alaska)[39] and 2022 (Southwest Alaska)[227] burned large areas in places where fire was rare or with atypical severity, as has been seen in other parts of the western US (Focus on Western Wildfires).[40] Overwintering fires, or "zombie" fires, which occur when uncharacteristically severe burning in hot, dry summers results in burning the following fire season, may also be increasing in the Arctic[228] and Alaska.[40] Permafrost thaw, including thermokarst (ground slumps or cave-ins)[229,230] and lake drainage,[231,232,233,234] is accelerating due to warming (e.g., Douglas et al. 2021[49]), particularly with recent wildfires[235,236] and uncharacteristically warm precipitation events.[237] These changes are projected to affect Arctic ecosystems and hydrology in important ways.[238] Across central and northern Alaska, changes in disturbance, vegetation productivity, and permafrost will affect the region's role in the global carbon cycle.[239,240] Current evidence suggests that carbon emissions from thawing permafrost[241] will exceed the carbon captured by increased vegetation productivity.

## Box 29.5. A New Era for Pacific Salmon Research in Alaska

When aquatic ecologist Vanessa von Biela's career started in 2007, it was still a "warmer is better" era for Alaska's salmon in their cooler northern range extent. Over the last decade, however, she has been among a group of scientists and local people who have found that salmon are reaching climate-driven tipping points. Stressful conditions for salmon include warm years with poor marine feeding,[21,242] heat stress or drought during freshwater spawning migrations,[23,139] and heavy fall rains during egg incubation.[243] Stressors are minimized in oceans and deep lakes where mixing maintains cooler waters, high nutrients, and productive feeding, as well as in places where glaciers and groundwater keep lakes and rivers cold.[29,244] Positive changes include new salmon habitat with retreat of glaciers and sea ice,[143,245] although Arctic winters still limit major northward shifts.[246] Salmon may be able to tolerate and adapt to stressful habitats, or they could move to find a better habitat patch. These options have important implications for people who depend on salmon. Investment in research by Vanessa, her colleagues, and local residents concerning new and emerging stressors can help inform climate-responsive management strategies that aim to improve outcomes for people.

### Chinook Salmon Research

**Research on the effects of heat on salmon can help scientists understand the effects of continued warming.**

**Figure 29.12.** Shown here is a chinook (king) salmon caught for non-lethal research on heat stress in a fish wheel on the Yukon River, July 2017. Photo credit: Shannon Waters-Dynes, USGS.

## Key Message 29.6

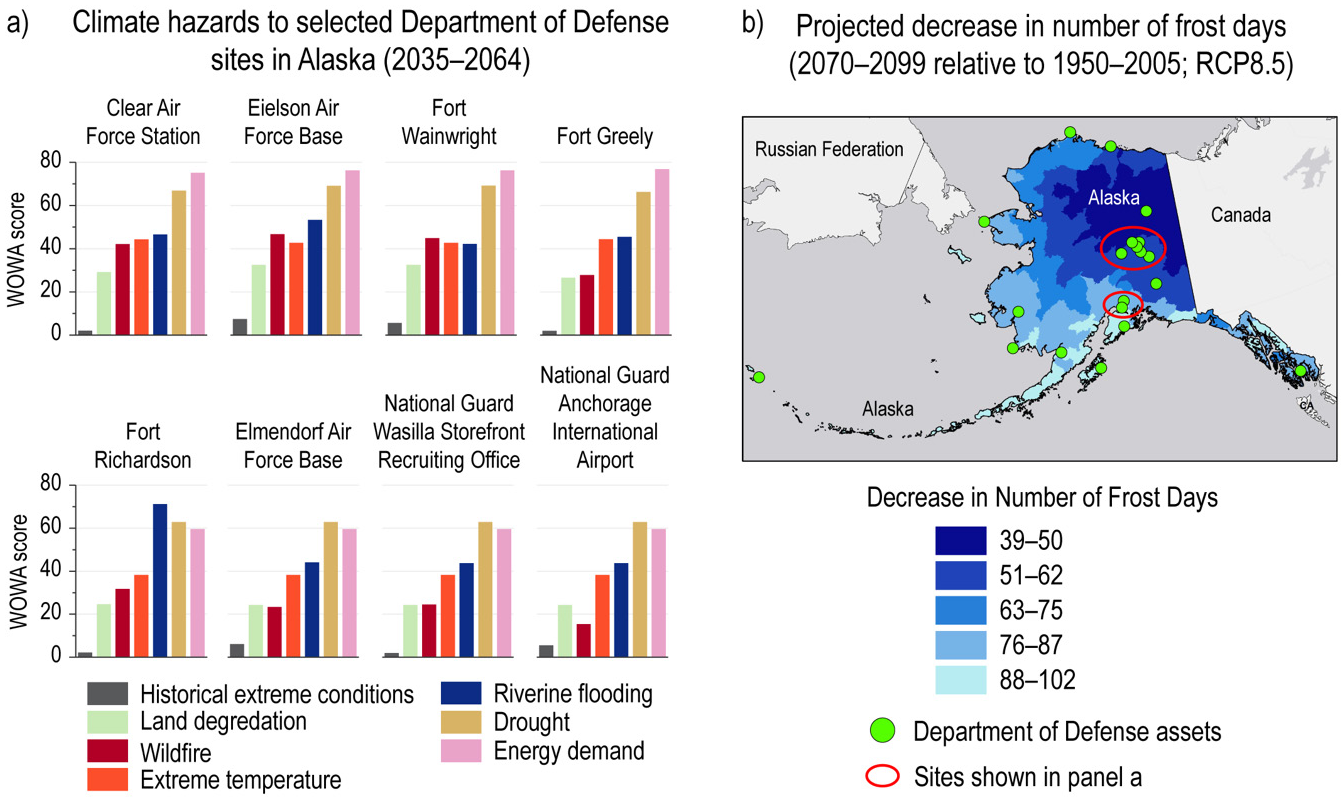
## Our Security Faces Greater Threats

Rapid climate-driven change in Alaska undermines many of the assumptions of predictability on which community, state, and national security are based (*high confidence*). Further change, especially in the marine environment with loss of sea ice, will create new vulnerabilities and requirements for security from multiple perspectives and at multiple scales (*high confidence*). Greater capacity for identifying and responding to threats has the potential to help reduce security risks in the Alaska region (*medium confidence*).

Security entails a sense of well-being and safety that is protected from or resilient to disruption. It is a combination of many interests and perspectives and reflects values such as a nation's sovereignty and integrity (KM 17.1) or a community's reliance on livelihoods and food sources that enable its people to thrive (KM 29.3; Box 11.1). Different interests are prioritized at the national/homeland, state, and community levels. Security actors at the national, state, and community level may face increasing demands for security services while also confronting the additional costs of climate change on physical infrastructure and operations, creating a double burden and making decisions even more challenging.

The Department of Defense (DoD) and Department of Homeland Security are impacted by climate change.[247] For example, coastal erosion, degrading permafrost, wildfire, and other climate effects will continue to impact DoD installations in Alaska (Figure 29.13).[248,249] At the state level, increasing wildfire risk and climate impacts to infrastructure increase management costs to the state.[176] Coastal erosion and thawing permafrost are affecting many coastal villages, reducing community security (KMs 9.2, 16.1, 21.3, 22.1, 29.4). Beyond Alaska, national policy responses to climate change, such as reducing dependence on fossil fuels, may impact energy sources, prices, and industry in Alaska, with potential effects on employment, household budgets, and environment.

## Climate Change Risks to Military Installations




**Climate change poses risks to military assets in Alaska.**

**Figure 29.13.** (**a**) The bar charts display climate risk for selected Department of Defense (DoD) sites in Alaska, based on the higher emission scenario for 2035–2064 data from the DoD Climate Assessment Tool. The y-axis is the weighted order–weighted average (WOWA) score of each site's exposure to aggregated climate hazards. For the Interior and Southcentral Alaska sites, drought and energy demand are the top climate hazards. At Fort Richardson, there is notably higher exposure to the riverine flooding climate hazard. In general, the scores are lower for the Southcentral region, indicating lower exposure to climate hazards. (**b**) Selected DoD sites in Alaska and projected reduction in frost days, illustrating the scale of the risk statewide (frost days are defined here as days with a minimum temperature at or below 32°F). The average annual number of frost days over the modeled baseline (1950–2005) ranges from 140–180 days in the Aleutian Islands to 260–290 days in the Brooks Range. In a higher greenhouse gas emissions scenario (RCP8.5), this will be reduced by about 20% in the Brooks Range and by over half in the Aleutians in 2070–2099. This will result in a longer ice-free season on the coast, leaving coastal communities vulnerable to storm surge more of the year. Portions of this figure include intellectual property of Esri and its licensors and are used under license. Copyright © 2020 Esri and its licensors. All rights reserved. Figure credit: USACE and DoD.

At the national level, DoD installations face a range of climate-associated hazards. For example, wildfire is a constant concern for military installations. Climate-driven drought, wind, and fire can affect operations, training, assets, and wildfire-suppression activities for DoD installations in a variety of ways.[248] The Alaska Fire Service and the US Army have recently been partnering to conduct springtime prescribed burns on military training lands in Alaska to reduce fire danger around military training targets.[250]

Climate impacts also generate national security concerns by altering maritime traffic in Alaska. Reductions in sea ice in Alaska waters enable more maritime activity. Changing and difficult-to-predict ice conditions, however, may require search-and-rescue activities that affect US Coast Guard presence and missions, as well as DoD civil support and military missions. Increasing maritime traffic in the Arctic[251] intersects with

the broader geopolitical context of competition with the People's Republic of China (PRC) and tension with Russia. The Russian government has been building (and rebuilding) military capability and capacity across its northern border, including sites near Alaska such as Wrangel Island.[252] The PRC has expressed interest in Arctic governance, resources, shipping lanes, and climate science.[253] In Alaska, recent concerns include PRC and Russian naval operations in the US exclusive economic zone; illegal, unreported, and unregulated fishing especially in the Bering Sea; and marine debris.[254]

Rising concern about climate change and increased geopolitical competition in the Arctic are reflected in recent Arctic-specific military strategy documents (e.g., DHS 2019;[255] DOD 2019;[248] USAF 2020[256]). In Alaska, the DoD is developing new capabilities and capacities in response to these changes. For example, as of spring 2022, Eielson Air Force Base has 54 F-35 aircraft, the largest concentration of the most technologically advanced airpower in the world.[257]

The state of Alaska faces direct and indirect climate change impacts to security with regard to crime, economic impacts (KMs 19.1, 19.3, 29.3), environmental impacts (KM 29.5), and state capacity to respond to such security challenges. Climate change is also increasing costs for the state, from firefighting to infrastructure maintenance (KM 29.4), with potential adverse ramifications for the state's ability to balance its budget and meet the needs of its citizens.[170]

At the community level, concerns center on food and environmental security (KM 29.2), as well as the safety of small boat operators and hunters navigating increasingly unpredictable and crowded marine and riverine environments (KM 15.1).[87] Changing sea and river ice conditions are increasing the physical risks for hunters and travelers. Climate change may also drive intensification of human offshore activities, such as increased commercial shipping, that generate additional risks such as accidents or spills.[258] Cultural practices are vital to well-being and security throughout Alaska (Box 29.3) but are often overlooked or minimized in fisheries management and in research on climate change and ecosystems.[75]

## Box 29.6. Tribal Perspectives on "Security"

For Tribes in Alaska, climate change is yet another reason to exercise leadership and sovereignty on their own behalf (KM 16.3). In Bristol Bay, for example, the Native Village of Port Heiden has created Meshik Farm to improve food security and would like to build a fish processing facility too. Says Jaclyn Christensen, Brownfield Coordinator for the Tribe, "I worry about my husband making long trips in dangerous waters when he's fishing, and we need an economic base for the community."[259]

The Knik Tribe in Southcentral Alaska is deeply involved in land management. As Theo Garcia, the Tribe's Environment and Natural Resources Director, explains, "We grow potatoes to provide food, we are cultivating native plants to support streambank restoration, and we are exploring ways to use waste heat to grow cheaper fodder for livestock."[260]

As conditions continue to change, being able to adjust is essential to security, through Tribes' own efforts and in partnership with others.

### Canned Red Salmon in Port Heiden

**Salmon is vital for food security in much of Alaska.**

**Figure 29.14.** A locally processed jar of red salmon sits in the sunshine in Port Heiden, Alaska, July 28, 2022. Photo credit: ©Jaclyn Christensen.

## Key Message 29.7

## Our Just and Prosperous Future Starts with Adaptation

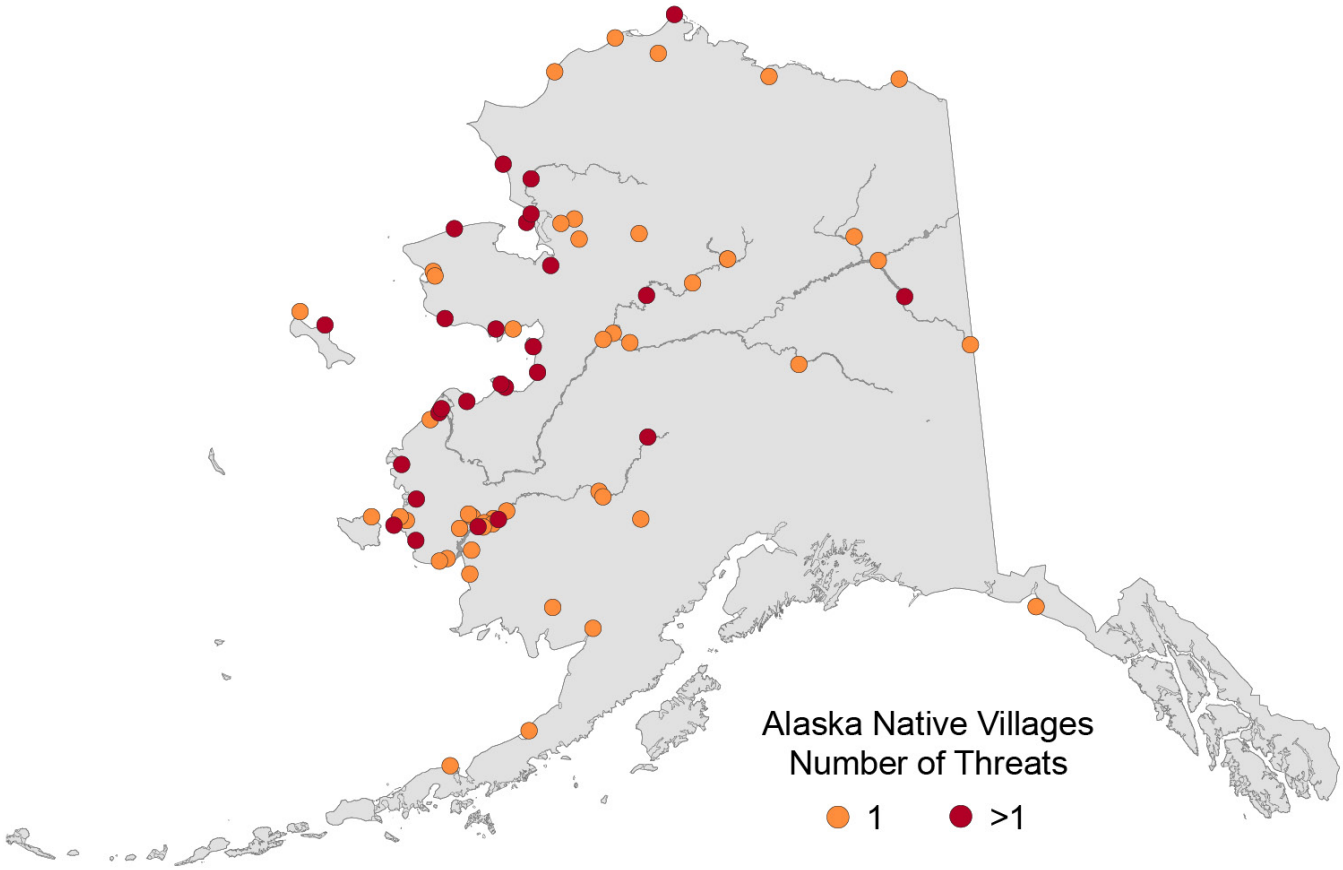
Local and regional efforts are underway around Alaska to prepare for and adapt to a changing climate (*high confidence*). The breadth of adaptation needed around the state will require substantial investment of financial resources and close coordination among agencies, including Tribal governments (*high confidence*). The effectiveness of adaptation planning and activities can be strengthened by addressing intersecting non-climate stressors, prioritizing the needs of the communities and populations experiencing the greatest impacts, building local capacity, and connecting adaptation efforts to economic and workforce development (*medium confidence*).

In recent years, Alaska has emerged as a leader of climate adaptation initiatives in the Arctic,[261] many of which have been implemented by regional entities and municipal, community, and Tribal governments.[262,263] Together, these efforts address climate change and intersecting societal challenges in ways that begin to lay a foundation for a just and prosperous Alaska. A wide variety of adaptation efforts has been undertaken statewide, from trainings and workshops to the implementation of hazard mitigation and climate action plans.[262,263,264] Despite widespread impacts (Figure 29.15), support for climate adaptation varies among communities,[263,265,266] and adaptation has not been a consistent priority for the state government (KM 31.1).[263,267,268] For many Alaskans, the ability to adapt to current and projected climate impacts is shaped by social and political factors such as food and water security, economic opportunity, and the capacity of governance systems (KM 31.4).[45,269,270,271]

Many of Alaska's Tribes have completed or are currently engaged in efforts that increase their ability to adapt to a changing climate (KM 16.3). These include applying for federal funding for climate resilience,[272] conducting risk assessments,[273] collaborating with researchers to bridge Western climate science and Indigenous Knowledge,[274] and developing and implementing community- and regional-level adaptation plans.[76,275,276] These activities are bolstered by the accumulated knowledge that has enabled Indigenous Peoples of Alaska and the Arctic to innovate and adapt to their changing environment for millennia.[270,277,278] The traditional values and practices of Alaska Native cultures focus on well-being, cultural continuity, and a holistic, integrated worldview (Figure 16.3).[75,270,279] They are often tied to components of adaptive capacity, such as environmental stewardship, communal pooling of subsistence resources, and mobility.[280,281,282,283,284] It is important to emphasize, however, that Alaska Native Peoples' ability to adapt does not mitigate the impacts of unprecedented environmental hazards or reduce the need to address the causes of climate change.

To achieve widely needed climate adaptation, communities must navigate a complex system of siloed federal agencies (Figure 29.16).[285,286,287] Overlapping local, borough, state, and federal jurisdictions can create confusing or conflicting policy directives and impede local adaptation efforts (KM 31.4).[277,288] Complex governance and resource management systems, many of which are imposed on Tribes through colonization, create challenges to adaptation efforts, which are most effective if they are timely, equitable, and community led. Also, the high adaptive capacity and self-reliance of Indigenous Peoples continues to be eroded by the ongoing impacts of colonization, including barriers to social networks and the transfer of Indigenous Knowledge.[277,279,289,290] Tribes are sovereign nations that require government-to-government consultation. Communities with strong collaboration among governing entities, including through coproduction of knowledge (research based on equitable and respectful partnerships), may be better able to respond to the adverse impacts of climate change through partnership and flexible management of natural resources.[279,281,285] Targeted coordination among and between federal, state, and Tribal entities would help build resilience to environmental threats.[286]

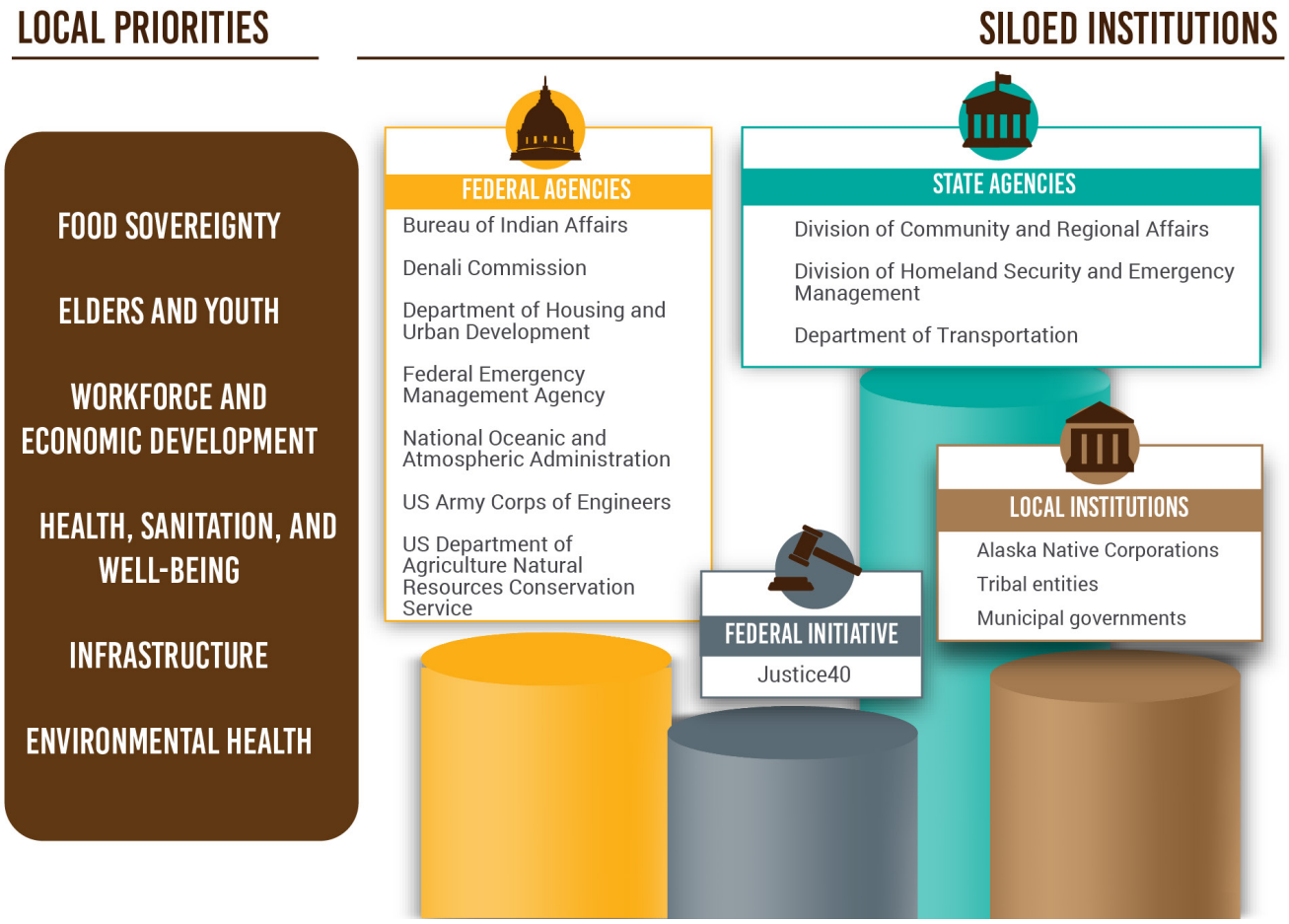
## Climate Threats Across Alaska




**Statewide assessments show extensive climate-related threats throughout Alaska.**

**Figure 29.15.** The map shows threats to Alaska Native villages from permafrost thaw, flooding, and erosion. Many communities face multiple threats, compounding the challenges they face. Adapted from GAO 2022.[286]

## Navigating Diverse Institutions to Meet Local and Regional Priorities




**Adaptation is a complex process, requiring expertise and engagement with multiple entities.**

**Figure 29.16.** Climate adaptation typically requires a wide range of expertise as well as engagement of those who are affected together with other entities, including but not limited to those listed in this figure.[286] Alaska Native corporations were created by the Alaska Native Claims Settlement Act of 1971.[291] Local priorities are holistic, involving integrated environmental and social issues. However, institutions on multiple levels are often siloed with specific priorities, which can lead to duplication of efforts and hamper local efforts. Figure credit: University of Alaska Fairbanks and Ocean Conservancy.

Although there are various sources of state and federal funding and technical assistance available to support municipal and Tribal climate adaptation in Alaska, the effectiveness of such efforts is hindered by institutional barriers and limited capacity across various levels of government (KMs 31.4, 31.6).[261,292] In both rural and non-rural communities, some residents have reported that climate adaptation has been impeded by a lack of local leadership or political will.[265,266,293] Many communities and organizations have stepped up to lead mitigation efforts and address the inequities compounded by climate change in the absence of consistent municipal and state action. At least four municipalities (Anchorage, Homer, Sitka, and Juneau) have adopted climate action plans,[264] with Fairbanks also currently at work on theirs. Seven Tribal governments from the Nome Eskimo Community to the Central Council of T'lingit and Haida have adopted climate action or adaptation plans.[264]

Community renewable energy initiatives like Thermalize Juneau and the Solarize initiatives in Anchorage, Fairbanks, Kenai, Mat-Su, and Palmer help residential and commercial property owners install solar capacity.[294,295,296] Local utilities such as Golden Valley Electric Association, Alaska Energy Light and Power,

and Chugach Electric Association have worked on several renewable energy projects.[297,298,299] Juneau Electric Vehicle Association specifically has worked to electrify public and personal transport in the region.[300] Many communities around the state are building local community-supported agriculture markets, shared gardens, and supply boxes to supplement neighborhoods farther away from urban grocery stores.[301] Tribal governments in Interior and Southwest Alaska delivered salmon to residents impacted by the Yukon–Kuskokwim salmon crash.[302]

Climate change can lead to divergent goals. While there are potential economic opportunities of a warming Arctic, such as increased marine traffic, growth in tourism, and resource extraction, considerations of relevant climate-related risks are not consistently incorporated into regulatory and planning processes.[266,269] For example, across coastal Alaska, communities are increasingly reliant on hard structures, such as seawalls and shoreline reinforcement. These structural adaptations can provide a sense of security, but they lack the flexibility, long-term sustainability, and cost effectiveness of regulatory and ecosystem-based approaches.[303]

Climate impacts are being experienced within the larger context of social, political, and economic change in the Arctic (KM 20.2).[281] Non-climate stressors such as food insecurity (KMs 29.1, 29.3, 29.5), limited employment (KM 29.3), substandard housing (KM 29.1), aging infrastructure (KM 29.4), limited access to healthcare (KM 29.1), the high cost of living in remote areas (KM 29.2), and limited search-and-rescue capability (KM 29.6) can affect a community's capacity and ability to pursue climate adaptation.[269,304,305] By identifying and addressing the intersections of climate risk and social and economic vulnerability, decision-makers can develop and implement adaptation initiatives that are scalable, innovative, and/or transformational.[266]

The need to center adaptation actions around and support Indigenous and local values, knowledge, and priorities has been widely identified as a critical component of community-based adaptation (KM 16.2).[45,269,270,285,289,306,307,308] In addition to integrating multiple knowledge systems and building workforce development and Tribal capacity for climate resilience,[309] climate adaptation efforts can be strengthened by fostering partnerships among diverse groups and supporting community-based leadership and monitoring.[45,267,285] This need is recognized in White House guidance to federal agencies.[310]

Education for many audiences has long been an essential component of adaptation in Alaska. Numerous educational efforts in Alaska are bringing climate change information and understanding to K–12 students, undergraduate and graduate students, educators, and community members. The Global Learning and Observations to Benefit the Environment (GLOBE) program has engaged more than 1,400 rural and urban Alaska teachers and over 20,000 students in climate change learning and citizen science in a culturally sustaining way since 1996.[311,312,313] Scientists have used Alaska students' GLOBE data.[314,315] The Arctic and Earth STEM Integrating GLOBE and NASA project braids Indigenous and Western science to engage formal and informal educators, community members, and youth in projects relevant to their communities[316], in partnership with the Association of Interior Native Educators. Other community/citizen science projects related to climate change focus on Alaska berries, freshwater ice, snow depth, and coastal community observations and knowledge.[317] Climate education efforts for adults include an online course exploring climate change in Arctic environments, community training in the Alaska Tribal Resilience Learning Network through the Alaska Climate Adaptation Science Center, and peer-to-peer learning and knowledge exchange in the community-led relocation, managed retreat, and protect-in-place coordinator cohort. The Scenarios Network for Alaska and Arctic Planning provides downscaled climate data, while the Alaska Center for Climate Assessment and Policy provides climate and weather webinars, graphics, and tools. New initiatives are also being developed.[318]

## Box 29.7. Tribal Adaptation to Climate Change

Threats to traditional foods are existential concerns for Tribal communities:

> *We're at a tipping point that people need to learn how to spell food sovereignty. — Dune Lankard, Eyak Athabascan, Copper River Delta (interview with Willow Hetrick, December 16, 2020).*[319]

Food sovereignty includes the ability of communities to determine the quantity and quality of food that they consume by controlling how their food is produced and distributed. To meet this need, Chugach Regional Resources Commission (CRRC) and one of its divisions, the Alutiiq Pride Marine Institute (APMI), incorporate Indigenous Knowledge, Tribal perspectives, and Western scientific methods. To address health concerns, the harmful algal bloom program analyzes weekly water samples and warns Tribal governments of any health concerns. To bolster regionally important food sources, they place young clams on beaches with dwindling clam populations and are extending that effort to bidarkis (the local name for black leather chitons, *Katharina tunicata*). To help reduce the effects of carbon dioxide emissions, CRRC and APMI are developing kelp farming as a mitigator of ocean acidification effects, a carbon sink, and a potential source of income. These efforts show what can be accomplished with dedication and collaboration.

### Harvesting Kelp in Prince William Sound

**Kelp farming is an adaptation action that can reduce the impacts of ocean acidification, take up carbon dioxide, and provide income.**

**Figure 29.17.** Kelp is being harvested on a boat in Prince William Sound, Alaska, May 15, 2022. Photo credit: ©Emily Mailman.

# Traceable Accounts

## *Process Description*

The author team reviewed the Alaska chapters in previous National Climate Assessments (NCAs) and considered the guidance from NCA leadership to make NCA5 "people-centered." The team recognized three broad topics: rapid biophysical change, compounding societal effects, and adaptation efforts. From these, the team developed seven areas for Key Messages and identified a number of themes to emphasize throughout the chapter, tying together the material in each Key Message. The team then reviewed the available information (as detailed below for each Key Message) to write the chapter. Where necessary, the team has cited reports and other non-peer-reviewed sources for specific information that is not available elsewhere. The author team agreed that the sources were credible and appropriate for the purposes for which they were cited. The team has not included likelihood statements (*very likely*, *unlikely*, etc.) because there was not a quantitative basis for doing so (Guide to the Report).

Key Messages from previous NCAs, and the overall guidance from NCA leadership, helped identify major areas where expertise would be needed. Diversity of age, race, gender, discipline, and perspective were also considered in selecting the author team, along with the ability to think broadly about connections among aspects of climate change. The chapter lead author, federal coordinating lead author, and agency chapter lead authors compiled a list of candidates and asked other organizations to suggest names so as to broaden the search. Once several persons were recruited as chapter authors, they too were asked about gaps in the team's collective expertise, and additional needs were identified along with candidates to address those needs.

The author team met twice monthly to discuss the chapter contents and the writing process. Through these meetings, the team achieved consensus on the approach to take and then on the contents as the team wrote and revised. The team held an online public engagement workshop on January 12, 2022, with approximately 175 persons registered and a maximum of about 90 participants at any given time. The workshop had a wide range of participants, including Indigenous community leaders, academic researchers, government agency personnel, individuals in the private sector, and members of the public. The team also conducted other outreach meetings and workshops to reach specific audiences, such as through the Alaska Forum on the Environment and the Interagency Arctic Research Policy Committee.

## Key Message 29.1

## Our Health and Healthcare Are at Risk

### Description of Evidence Base

A great deal of research has been done on health status, access to healthcare, and other aspects of health in Alaska (e.g., Hennessey et al. 2008;[67] Thomas et al. 2015;[60] Eichelberger 2010;[59] Hahn et al. 2021[82]). The context in which climate change affects health is thus generally well established (KM 15.1).[61] Attention to mental health and community health has been growing in recent years, providing an increasingly firm foundation for this Key Message (KM 15.1).[74,75,76] Research specifically on the implications of climate change for health and mental health has been more limited in Alaska. The findings of that research are generally consistent.

### Major Uncertainties and Research Gaps

Much of the literature about climate change and health in Alaska has focused on what is to be expected as the climate continues to warm. Evidence of the actual health effects that are occurring at present is less robust, although what does exist is consistent across studies. There is also a lack of studies documenting

health effects, especially mental and community health effects specifically tied to factors related to climate change, and determining effective public health responses. More work can be done to document Indigenous Knowledge with regard to health and mental health in Alaska.

### Description of Confidence and Likelihood

Health disparities in Alaska are all too well documented (e.g., Cochran et al. 2013;[55] Thomas et al. 2015;[60] Eichelberger 2010;[59] Sohns et al. 2021[56]). Further challenges to health and to access to healthcare will compound those disparities. This can be said with *high confidence*. There is some evidence for the expected effects of climate-driven hazards and emerging diseases (e.g., Witmer et al. 2022;[84] Hahn et al. 2020,[83] Yoder 2018;[57] Huntington et al. 2021[87]), and the state's experience with COVID-19 has amply illustrated what a new disease can do (e.g., Wong et al. 2022;[64] Eichelberger et al. 2021[62]). The course of climate change in regard to health, however, has many uncertainties, and thus the team has *medium confidence* in the second statement in the Key Message. Similarly, improved health surveillance and healthcare access can be expected to contribute to resilience statewide, but further experience and evidence are needed to show that this is the case. Thus, the team has *medium confidence* in the final statement of the Key Message.

## Key Message 29.2

## Our Communities Are Navigating Compounding Stressors

### Description of Evidence Base

Considerable work has been done to document many aspects of Alaska's communities, including social, economic, cultural, physical, and other research.[96,97,107,108,109] Some work has been done, especially in Alaska Native communities, to document observations of and effects from climate change. The findings are in broad agreement that much is changing rapidly, with far-reaching effects on communities. The details vary from place to place and study to study. There is little disagreement in the literature base. Far less work is available about other segments of the population in Alaska, making it difficult to determine whether there are racial and ethnic disparities in climate change exposure and effects among groups other than Alaska Natives.

### Major Uncertainties and Research Gaps

Little is known about the effectiveness of responses and adaptations to climate change among Alaska Native communities. For other demographic groups, and for Alaska Natives in urban environments, more research would be required overall to better assess how climate change is affecting and is expected to affect these communities. More work can be done to document Indigenous Knowledge with regard to community well-being in Alaska.

### Description of Confidence and Likelihood

The detailed demographic and other evidence that is available concerning community well-being in Alaska is consistent and has been documented repeatedly in the scientific literature and in reports by Tribal and federal agencies, giving the team *high confidence* in the statements in the Key Message. Risks to infrastructure are well known and not in dispute. The benefits of adaptation are addressed in greater detail in Key Message 29.7 and have been established repeatedly around the state.

## Key Message 29.3

## Our Livelihoods Are Vulnerable Without Diversification

### Description of Evidence Base

The state and federal governments regularly collect relevant economic data, providing a firm foundation for understanding Alaska's livelihoods and employment.[96,120,121,122,123] Similarly, much work has been done to document subsistence harvests, providing reliable and consistent figures for production and participation in this vital sector of the economy of rural Alaska. The effects of climate change have been considered for many economic sectors, although to differing degrees. Not surprisingly, those sectors such as fishing that are perceived as being at highest risk from climate change have received the most attention. The findings to date are broadly consistent, allowing for differences in climate change exposure across different sectors.

### Major Uncertainties and Research Gaps

Much of the work to date has focused on sectors perceived as vulnerable to climate change, including fishing and subsistence. Less has been done to examine areas of potential new opportunity (e.g., in agriculture), and more research could improve understanding of the effectiveness of various responses and adaptations to changing climate.

There is uncertainty about the economic consequences of climate-driven declines in commercial and subsistence harvest because the impacts of climate change can be moderated by economic dynamics and alternative harvest opportunities.[125,126,143]

A major uncertainty regarding climate impacts on groundfish, salmon, and crab is the unknown influences of interacting processes and parameters, such as competition, predation, density dependence, food web structure, habitat availability, and harvest.[18,131,142,144] Thus, future research on the impacts of climate on groundfish, salmon, and crab should be interdisciplinary.

Another major topic that could benefit from future research is the mechanisms linking climate drivers to biological effects on salmon, groundfish, and crab.[134,137,320] Elucidation of the details of these mechanisms could help improve predictions of ecosystem change in the context of future climate change. In addition, spatial variation in ecosystem response to climate change lends uncertainty to predicting local impacts.[21,23]

More work can be done to document Indigenous Knowledge with regard to livelihoods and the factors that affect them in Alaska.

### Description of Confidence and Likelihood

Documentation of risks posed by climate change to resource-dependent livelihoods is extensive and consistent in the scientific literature and in government reports, giving the author team *high confidence* in the first statement of the Key Message. Looking to the future involves greater uncertainty, and thus the team has *medium confidence* in the second statement of the Key Message. The third statement is supported by the available literature, but there is not a great deal of it, giving the team *medium confidence*.

## Key Message 29.4

## Our Built Environment Will Become More Costly

### Description of Evidence Base

Many major assessments have been done concerning Alaska's built environment, including economic studies of the costs associated with climate change and the risks from coastal and riverbank erosion around the state.[170,171,173,174,181] The findings are consistent that costs will be high and that many communities face high risks. The timing of erosion and other damage is less certain, as is the effectiveness of various measures to slow or stop climate-driven effects.

### Major Uncertainties and Research Gaps

More work could improve understanding of the effectiveness of various responses to climate-driven damage to infrastructure. How response capacity can be created or provided, especially to remote communities, is an open question. The fact that models probably underestimate the actual costs and damages suggests another area for further work. These gaps contribute to uncertainty in estimates of the costs associated with infrastructure degradation, destruction, and collapse. More work can be done to document Indigenous Knowledge with regard to the built environment in Alaska. In addition to research gaps, knowledge fragmentation is a major hindrance to effective action. Reducing this fragmentation would require a greater effort to bring together scientists, community members and knowledge holders, and private businesses, especially engineering consulting firms that are already implementing practical solutions.

### Description of Confidence and Likelihood

There is little question about the damage being done to Alaska's infrastructure due to climate change and little doubt that more damage will occur. Thus, based on well-documented experiences around the state (e.g., some of the major university and government reports cited in the Key Message text, which are consistent with one another), the author team has *high confidence* in the first two statements of the Key Message concerning what effects climate change is having on infrastructure and the further effects that are expected. The third sentence, about planning and adaptation, is of *high confidence* due to the evidence that planning can work. The team notes here that the question remains as to what is required to implement designs and ideas for protecting infrastructure to withstand the effects of climate change.

## Key Message 29.5

## Our Natural Environment Is Transforming Rapidly

### Description of Evidence Base

Changes in Alaska's marine, terrestrial and freshwater ecosystems, including effects of climate on species ranges, species viability, community structure, ecosystem structure and function, and landscapes and riverscapes are extensively documented in the scientific literature.[1,39,143,192,198]

The strong climatic controls implicated in many, though not all, of these changes may negatively affect the abundance and/or quality of ecosystem goods and services, such as ice transportation or many ocean and anadromous fisheries, but projections of these impacts are easier for some goods and services than others. Confidence is higher for those impacts that are directly mediated by physical drivers (e.g., temperature effects on sea ice[45] or snowpack[46]) than those with complex drivers (multiple climate drivers and ecological interactions, such as berry production.[160]

The fact that some of the stressors are non-climatic and can respond to management choices or strategies indicates the possibility of avoiding some potential impacts through management. The literature on alternative strategies is limited; this is where synthetic and logical arguments can be made on the scientific information describing impacts and plausible future. But it is yet uncertain which management choices would be potentially effective, how they would be implemented, and whether they would be sufficient to decrease impacts.

## Major Uncertainties and Research Gaps

As with many impacts of climatic change, attribution of the fraction of the response due directly to climatic change is challenging. Much of the work is correlative rather than deterministic, and in Alaska, the datasets that exist for attribution work are severely limited compared to places in the contiguous United States (CONUS) because of the scarcity of long-term observational datasets that can be used for training downscaling methods. Thus, datasets downscaled from CMIP6 models were not available for Alaska when they were available for CONUS. Downscaling methodology that would accelerate attribution research is also limited. However, even perfect historical and future climatologies would not eliminate uncertainty—useful attribution and projections depend on strong impacts modeling and appropriate bridging to resource management, and understanding impacts on goods and services is not the same as direct modeling of species, community, landscape, and ocean impacts. A major research gap is adequate long-term physical and biological monitoring data needed to support and improve model forecasts. More work can be done to document Indigenous Knowledge with regard to the natural environment in Alaska, keeping in mind important questions of who is doing the documentation, how, and for what purpose. The considerations have implications for climate justice and Indigenous rights. Additionally, there is a need to better coordinate and improve accessibility of existing data to help identify data needs as well as make more effective use of what is already known.

## Description of Confidence and Likelihood

A great deal of scientific research, as reported widely in the scholarly literature, has examined ecological change in detail around Alaska. The confidence in ecological change is *high* and not *very high* because other non-climatic factors (such as development and other changes in land use) also contribute to ecosystem change and/or documentation of climate-driven change has yet to emerge for some observed changes.

Confidence concerning ecosystem goods and services is *medium* because 1) although impacts modeling for many species and processes indicates this is probably true, impacts modeling for goods and services is limited compared to direct physical and ecological impacts; and 2) uncertainty in both climate futures and ecosystem responses is large enough that specific predictions are elusive. Although the reasoning is sound, there is a limited body of peer-reviewed published evidence.

Confidence in the ability of careful management to help address climate concerns in the context of other needs and aims is *medium* because there is limited peer-reviewed literature documenting that climate-relevant management practices would be adopted. However, examples exist.

## Key Message 29.6

## Our Security Faces Greater Threats

### Description of Evidence Base

Some research and planning have been done by the branches of the armed services to assess the hazards from climate change in Alaska.[248] Additionally, some work has been done to assess hazards to civilian forms of security, including food security.[75,87,251,254] The literature is consistent in identifying multiple hazards and high uncertainties, which exacerbate risks to security by impeding the ability to plan effectively and efficiently.

### Major Uncertainties and Research Gaps

Obvious risks such as coastal erosion and damage from thawing permafrost are well documented. Some other risks, such as the potential for wildfires and associated smoke to disrupt airborne operations, have been recognized. The assessment of many other risks, however, remains speculative and would benefit from further study. Of note here is the unknown degree to which climate change will alter, rather than merely have a modest influence on, geopolitical concerns and national security threats. More work can be done to document Indigenous Knowledge with regard to the various aspects of security in Alaska.

### Description of Confidence and Likelihood

Due to the extent and nature of climate change, as documented in numerous academic and government studies, there is *high confidence* that a changing climate has the potential to alter Alaska's security at scales from local to national. Likewise, there is little question—and thus *high confidence*—that further change will continue to create this hazard. Exactly how the appraised risks will turn into actual effects is less certain in the available literature, giving *medium confidence* in the ability to develop and put in place effective response strategies.

## Key Message 29.7

## Our Just and Prosperous Future Starts with Adaptation

### Description of Evidence Base

Peer-reviewed academic research that analyzes or documents climate adaptation successes and challenges is less prevalent than other sources such as online portals, gray and white literature, published adaptation plans, and other reliable sources of information. However, the body of literature is growing, and all of these sources are relatively consistent in their content. Several non-climate stressors have been identified in peer-reviewed literature as factors that can affect a population's ability to adapt to climate change.[270,304,305,321] Building local capacity and connecting adaptation efforts to economic and workforce development are emerging topics that have less evidence base in existing publications,[322,323] but the authors felt it was important to include these issues based on observations and lived experience.

### Major Uncertainties and Research Gaps

As noted above, existing research gaps related to climate adaptation and planning exist in the academic literature; however, there are several areas of agreement among white and gray literature and lived experience, as documented in other credible sources. Research focusing on community values, priorities, and needs, including workforce development, is just emerging. Very little research has been done evaluating the implementation of adaptation efforts, especially through Indigenous evaluation methodol-

ogies.[324] More work can be done to document Indigenous Knowledge with regard to resilience and climate response in Alaska. Additional work can also be done to learn from what is and is not working in ongoing adaptation activities.

## Description of Confidence and Likelihood

There is strong evidence from many reports and studies (see citations in the Key Message text), and thus *high confidence*, that local and regional adaptation efforts are underway and that more have been funded. The new influx of federal funding opportunities is expected to provide much-needed support, building on previous investments in rural Alaska, which together give *high confidence* that the demand for investment is substantial. As of this writing, little work has been done, however, to establish locally acceptable metrics and evaluation plans to assess the actual impact of funding influx. Given that research focusing on community values, priorities and needs, including workforce development, is just emerging, the final sentence of the Key Message has been assigned *medium confidence*.

# References


1. Ballinger, T.J., U.S. Bhatt, P.A. Bieniek, B. Brettschneider, R.T. Lader, J.S. Littell, R.L. Thoman, C.F. Waigl, J.E. Walsh, and M.A. Webster, 2023: Alaska terrestrial and marine climate trends, 1957–2021. *Journal of Climate*, **36**, 4375–4391. https://doi.org/10.1175/jcli-d-22-0434.1

2. Markon, C., S. Gray, M. Berman, L. Eerkes-Medrano, T. Hennessy, H. Huntington, J. Littell, M. McCammon, R. Thoman, and S. Trainor, 2018: Ch. 26. Alaska. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1185–1241. https://doi.org/10.7930/nca4.2018.ch26

3. Stabeno, P.J. and S.W. Bell, 2019: Extreme conditions in the Bering Sea (2017–2018): Record-breaking low sea-ice extent. *Geophysical Research Letters*, **46** (15), 8952–8959. https://doi.org/10.1029/2019gl083816

4. Anderson, D.M., E. Fensin, C.J. Gobler, A.E. Hoeglund, K.A. Hubbard, D.M. Kulis, J.H. Landsberg, K.A. Lefebvre, P. Provoost, M.L. Richlen, J.L. Smith, A.R. Solow, and V.L. Trainer, 2021: Marine harmful algal blooms (HABs) in the United States: History, current status and future trends. *Harmful Algae*, **102**, 101975. https://doi.org/10.1016/j.hal.2021.101975

5. Bond, N.A., M.F. Cronin, H. Freeland, and N. Mantua, 2015: Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, **42** (9), 3414–3420. https://doi.org/10.1002/2015gl063306

6. Qi, D., L. Chen, B. Chen, Z. Gao, W. Zhong, Richard A. Feely, Leif G. Anderson, H. Sun, J. Chen, M. Chen, L. Zhan, Y. Zhang, and W.-J. Cai, 2017: Increase in acidifying water in the western Arctic Ocean. *Nature Climate Change*, **7** (3), 195–199. https://doi.org/10.1038/nclimate3228

7. Bathke, D.J., H.R. Prendeville, A. Jacobs, R. Heim, R. Thoman, and B. Fuchs, 2019: Defining drought in a temperate rainforest. *Bulletin of the American Meteorological Society*, **100** (12), 2665–2668. https://doi.org/10.1175/bams-d-19-0223.1

8. NWS, n.d.: Historic Drought in a Rainforest: Southeast Alaska (2017–2019). National Oceanic and Atmospheric Administration, National Weather Service, Juneau, AK. https://noaa.maps.arcgis.com/apps/MapJournal/index.html?appid=8ce2db39efde4e589ec66692be45f90a

9. Yates, S., 2020: Extreme Rain Brings Flurry of Landslides. LEO Network. https://www.leonetwork.org/en/posts/show/09e0b101-1489-44e1-8fea-221308a9661a

10. Glomsrod, S., T. Wei, R. Macdonald, L. Lindholt, S. Goldsmith, and T. Matthiasson, 2021: Ch. 4. Arctic economies within the Arctic nations. In: *The Economy of the North–ECONOR 2020*. Glomsrød, S., G. Duhaime, and I. Aslaksen, Eds. Arctic Council Secretariat, Tromso, Norway, 51–100. http://hdl.handle.net/11374/2611

11. Danielson, S.L., O. Ahkinga, C. Ashjian, E. Basyuk, L.W. Cooper, L. Eisner, E. Farley, K.B. Iken, J.M. Grebmeier, L. Juranek, G. Khen, S.R. Jayne, T. Kikuchi, C. Ladd, K. Lu, R.M. McCabe, G.W.K. Moore, S. Nishino, F. Ozenna, R.S. Pickart, I. Polyakov, P.J. Stabeno, R. Thoman, W.J. Williams, K. Wood, and T.J. Weingartner, 2020: Manifestation and consequences of warming and altered heat fluxes over the Bering and Chukchi Sea continental shelves. *Deep Sea Research Part II: Topical Studies in Oceanography*, **177**, 104781. https://doi.org/10.1016/j.dsr2.2020.104781

12. Walsh, J.E., R.L. Thoman, U.S. Bhatt, P.A. Bieniek, B. Brettschneider, M. Brubaker, S. Danielson, R. Lader, F. Fetterer, K. Holderied, K. Iken, A. Mahoney, M. McCammon, and J. Partain, 2018: The high latitude marine heat wave of 2016 and its impacts on Alaska. *Bulletin of the American Meteorological Society*, **99** (1), S39–S43. https://doi.org/10.1175/bams-d-17-0105.1

13. Pilcher, D.J., D.M. Naiman, J.N. Cross, A.J. Hermann, S.A. Siedlecki, G.A. Gibson, and J.T. Mathis, 2019: Modeled effect of coastal biogeochemical processes, climate variability, and ocean acidification on aragonite saturation state in the Bering Sea. *Frontiers in Marine Science*, **5**, 508. https://doi.org/10.3389/fmars.2018.00508

14. Carvalho, K.S., T.E. Smith, and S. Wang, 2021: Bering Sea marine heatwaves: Patterns, trends and connections with the Arctic. *Journal of Hydrology*, **600**, 126462. https://doi.org/10.1016/j.jhydrol.2021.126462

15. Cheung, W.W.L., T.L. Frölicher, V.W.Y. Lam, M.A. Oyinlola, G. Reygondeau, U. Rashid Sumaila, T.C. Tai, L.C.L. Teh, and C.C.C. Wabnitz, 2021: Marine high temperature extremes amplify the impacts of climate change on fish and fisheries. *Science Advances*, **7** (40), 1–16. https://doi.org/10.1126/sciadv.abh0895

16. Bachand, C.L. and J.E. Walsh, 2022: Extreme precipitation events in Alaska: Historical trends and projected changes. *Atmosphere*, **13** (3), 388. https://doi.org/10.3390/atmos13030388

17. Lader, R., U.S. Bhatt, J.E. Walsh, and P.A. Bieniek, 2022: Projections of hydroclimatic extremes in southeast Alaska under the RCP8.5 scenario. *Earth Interactions*, **26** (1), 180–194. https://doi.org/10.1175/ei-d-21-0023.1

18. Hunt Jr., G.L., E.M. Yasumiishi, L.B. Eisner, P.J. Stabeno, and M.B. Decker, 2020: Climate warming and the loss of sea ice: The impact of sea-ice variability on the southeastern Bering Sea pelagic ecosystem. *ICES Journal of Marine Science*, **79** (3), 937–953. https://doi.org/10.1093/icesjms/fsaa206

19. SeaBank, 2020: SeaBank Annual Report 2020. Alaska Sustainable Fisheries Trust, Sitka, AK, 129 pp. https://thealaskatrust.org/about-seabank

20. Siddon, E., 2021: Ecosystem Status Report 2021: Eastern Bering Sea, Stock Assessment and Fishery Evaluation Report. North Pacific Fishery Management Council, Anchorage, AK, 249 pp. https://apps-afsc.fisheries.noaa.gov/refm/docs/2021/ebsecosys.pdf

21. Suryan, R.M., M.L. Arimitsu, H.A. Coletti, R.R. Hopcroft, M.R. Lindeberg, S.J. Barbeaux, S.D. Batten, W.J. Burt, M.A. Bishop, J.L. Bodkin, R. Brenner, R.W. Campbell, D.A. Cushing, S.L. Danielson, M.W. Dorn, B. Drummond, D. Esler, T. Gelatt, D.H. Hanselman, S.A. Hatch, S. Haught, K. Holderied, K. Iken, D.B. Irons, A.B. Kettle, D.G. Kimmel, B. Konar, K.J. Kuletz, B.J. Laurel, J.M. Maniscalco, C. Matkin, C.A.E. McKinstry, D.H. Monson, J.R. Moran, D. Olsen, W.A. Palsson, W.S. Pegau, J.F. Piatt, L.A. Rogers, N.A. Rojek, A. Schaefer, I.B. Spies, J.M. Straley, S.L. Strom, K.L. Sweeney, M. Szymkowiak, B.P. Weitzman, E.M. Yasumiishi, and S.G. Zador, 2021: Ecosystem response persists after a prolonged marine heatwave. *Scientific Reports*, **11** (1), 6235. https://doi.org/10.1038/s41598-021-83818-5

22. ACRC, 2020: 2019 Alaska Climate Review. Alaska Climate Research Center, 27 pp. https://akclimate.org/annual_report/2019-annual-report/

23. von Biela, V.R., C.J. Sergeant, M.P. Carey, Z. Liller, C. Russell, S. Quinn-Davidson, P.S. Rand, P.A.H. Westley, and C.E. Zimmerman, 2022: Premature mortality observations among Alaska's Pacific salmon during record heat and drought in 2019. *Fisheries*, **47** (4), 157–168. https://doi.org/10.1002/fsh.10705

24. AMAP, 2018: *AMAP Assessment 2018: Arctic Ocean Acidification*. Arctic Monitoring and Assessment Programme, Tromsø, Norway, 187 pp. https://www.amap.no/documents/doc/amap-assessment-2018-arctic-ocean-acidification/1659

25. Cheng, W., A.J. Hermann, A.B. Hollowed, K.K. Holsman, K.A. Kearney, D.J. Pilcher, C.A. Stock, and K.Y. Aydin, 2021: Eastern Bering Sea shelf environmental and lower trophic level responses to climate forcing: Results of dynamical downscaling from CMIP6. *Deep Sea Research Part II: Topical Studies in Oceanography*, **193**, 104975. https://doi.org/10.1016/j.dsr2.2021.104975

26. Frölicher, T.L., E.M. Fischer, and N. Gruber, 2018: Marine heatwaves under global warming. *Nature*, **560** (7718), 360–364. https://doi.org/10.1038/s41586-018-0383-9

27. Hermann, A.J., K. Kearney, W. Cheng, D. Pilcher, K. Aydin, K.K. Holsman, and A.B. Hollowed, 2021: Coupled modes of projected regional change in the Bering Sea from a dynamically downscaling model under CMIP6 forcing. *Deep Sea Research Part II: Topical Studies in Oceanography*, **194**, 104974. https://doi.org/10.1016/j.dsr2.2021.104974

28. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

29. Shaftel, R., S. Mauger, J. Falke, D. Rinella, J. Davis, and L. Jones, 2020: Thermal diversity of salmon streams in the Matanuska-Susitna Basin, Alaska. *Journal of the American Water Resources Association*, **56** (4), 630–646. https://doi.org/10.1111/1752-1688.12839

30. O'Neel, S., C. McNeil, L.C. Sass, C. Florentine, E.H. Baker, E. Peitzsch, D. McGrath, A.G. Fountain, and D. Fagre, 2019: Reanalysis of the US Geological Survey benchmark glaciers: Long-term insight into climate forcing of glacier mass balance. *Journal of Glaciology*, **65** (253), 850–866. https://doi.org/10.1017/jog.2019.66

31. Wolken, G.J., B. Wouters, M. Sharp, L.M. Andreassen, D. Burgess, J. Kohler, and B. Luks, 2020: NOAA Arctic Report Card 2020: Glaciers and Ice Caps Outside Greenland. National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, 8 pp. https://doi.org/10.25923/nwqq-8736

32. Romanovsky, V.E., S.L. Smith, K. Isaksen, K.E. Nyland, A.L. Kholodov, N.I. Shiklomanov, D.A. Streletskiy, L.M. Farquharson, D.S. Drozdov, G.V. Malkova, and H.H. Christiansen, 2020: [The Arctic] terrestrial permafrost [in "State of the Climate in 2019"]. *Bulletin of the American Meteorological Society*, **101** (8), S265–S271. https://doi.org/10.1175/bams-d-20-0086.1

33. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

34. Grabinski, Z. and H.R. McFarland, 2020: Alaska's Changing Wildfire Environment [Outreach Booklet]. University of Alaska Fairbanks, International Arctic Research Center, Alaska Fire Science Consortium. https://www.frames.gov/afsc/acwe

35. Redilla, K., S. Pearl, P. Bieniek, and J. Walsh, 2019: Wind climatology for Alaska: Historical and future. *Atmospheric and Climate Sciences*, **9**, 683–702. https://doi.org/10.4236/acs.2019.94042

36. Hartmann, B. and G. Wendler, 2005: The significance of the 1976 Pacific climate shift in the climatology of Alaska. *Journal of Climate*, **18** (22), 4824–4839. https://doi.org/10.1175/jcli3532.1

37. Walsh, J.E. and B. Brettschneider, 2019: Attribution of recent warming in Alaska. *Polar Science*, **21**, 101–109. https://doi.org/10.1016/j.polar.2018.09.002

38. Dobricic, S., S. Russo, L. Pozzoli, J. Wilson, and E. Vignati, 2020: Increasing occurrence of heat waves in the terrestrial Arctic. *Environmental Research Letters*, **15** (2), 024022. https://doi.org/10.1088/1748-9326/ab6398

39. Bhatt, U.S., R.T. Lader, J.E. Walsh, P.A. Bieniek, R. Thoman, M. Berman, C. Borries-Strigle, K. Bulock, J. Chriest, M. Hahn, A.S. Hendricks, R. Jandt, J. Little, D. McEvoy, C. Moore, T.S. Rupp, J. Schmidt, E. Stevens, H. Strader, C. Waigl, J. White, A. York, and R. Ziel, 2021: Emerging anthropogenic influences on the Southcentral Alaska temperature and precipitation extremes and related fires in 2019. *Land*, **10** (1), 82. https://doi.org/10.3390/land10010082

40. Jandt, R. and A. York, 2021: Wildfire is transforming Alaska and amplifying climate change. *Scientific American*, **325** (4), 42–49. https://www.scientificamerican.com/article/wildfire-is-transforming-alaska-and-amplifying-climate-change/

41. Gutiérrez, J.M., R.G. Jones, G.T. Narisma, L.M. Alves, M. Amjad, I.V. Gorodetskaya, M. Grose, N.A.B. Klutse, S. Krakovska, J. Li, D. Martínez-Castro, L.O. Mearns, S.H. Mernild, T. Ngo-Duc, B. van den Hurk, and J.-H. Yoon, 2021: Atlas. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1927–2058. https://doi.org/10.1017/9781009157896.021

42. Iturbide, M., J. Fernández, J.M. Gutiérrez, J. Bedia, E. Cimadevilla, J. Díez-Sierra, R. Manzanas, A. Casanueva, J. Baño-Medina, J. Milovac, S. Herrera, A.S. Cofiño, D. San Martín, M. García-Díez, M. Hauser, D. Huard, and Ö. Yelekci. 2021: Repository Supporting the Implementation of Fair Principles in the IPCC WG1 Atlas. Zenodo. https://doi.org/10.5281/zenodo.3691645

43. Parding, K.M., A. Dobler, C.F. McSweeney, O.A. Landgren, R. Benestad, H.B. Erlandsen, A. Mezghani, H. Gregow, O. Räty, E. Viktor, J. El Zohbi, O.B. Christensen, and H. Loukos, 2020: GCMeval—An interactive tool for evaluation and selection of climate model ensembles. *Climate Services*, **18**, 100167. https://doi.org/10.1016/j.cliser.2020.100167

44. Bieniek, P.A., J.E. Walsh, R.L. Thoman, and U.S. Bhatt, 2014: Using climate divisions to analyze variations and trends in Alaska temperature and precipitation. *Journal of Climate*, **27** (8), 2800–2818. https://doi.org/10.1175/jcli-d-13-00342.1

45. Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, H. Ottersen, H. Pritchard, and E.A.G. Schuur, 2022: Ch. 3. Polar Regions. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Pörtner, H.O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 203–320. https://doi.org/10.1017/9781009157964.005

46. Littell, J.S., S.A. McAfee, and G.D. Hayward, 2018: Alaska snowpack response to climate change: Statewide snowfall equivalent and snowpack water scenarios. *Water*, **10** (5), 668. https://doi.org/10.3390/w10050668

47. Mudryk, L., M. Santolaria-Otín, G. Krinner, M. Ménégoz, C. Derksen, C. Brutel-Vuilmet, M. Brady, and R. Essery, 2020: Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. *Cryosphere*, **14** (7), 2495–2514. https://doi.org/10.5194/tc-14-2495-2020

48. Thoman, R.L., U.S. Bhatt, P.A. Bieniek, B.R. Brettschneider, M. Brubaker, S.L. Danielson, Z. Labe, R. Lader, W.N. Meier, G. Sheffield, and J.E. Walsh, 2020: The record low Bering Sea ice extent in 2018: Context, impacts, and an assessment of the role of anthropogenic climate change. *Bulletin of the American Meteorological Society*, **101** (1), S53–S58. https://doi.org/10.1175/bams-d-19-0175.1

49. Douglas, T.A., C.A. Hiemstra, J.E. Anderson, R.A. Barbato, K.L. Bjella, E.J. Deeb, A.B. Gelvin, P.E. Nelsen, S.D. Newman, S.P. Saari, and A.M. Wagner, 2021: Recent degradation of interior Alaska permafrost mapped with ground surveys, geophysics, deep drilling, and repeat airborne lidar. *Cryosphere*, **15** (8), 3555–3575. https://doi.org/10.5194/tc-15-3555-2021

50. Osterkamp, T.E., M.T. Jorgenson, E.A.G. Schuur, Y.L. Shur, M.Z. Kanevskiy, J.G. Vogel, and V.E. Tumskoy, 2009: Physical and ecological changes associated with warming permafrost and thermokarst in interior Alaska. *Permafrost and Periglacial Processes*, **20** (3), 235–256. https://doi.org/10.1002/ppp.656

51. Farquharson, L.M., V.E. Romanovsky, A. Kholodov, and D. Nicolsky, 2022: Sub-aerial talik formation observed across the discontinuous permafrost zone of Alaska. *Nature Geoscience*, **15** (6), 475–481. https://doi.org/10.1038/s41561-022-00952-z

52. Marino, E., 2015: *Fierce Climate, Sacred Ground: An Ethnography of Climate Change in Shishmaref, Alaska*. University of Alaska Press, Fairbanks, AK, 122 pp. https://upcolorado.com/university-of-alaska-press/item/5674-fierce-climate-sacred-ground

53. KTOO, 2018: Major earthquake damages buildings and roads in Anchorage. *KTOO Public Media*, November 30, 2018. https://www.ktoo.org/2018/11/30/6-7-magnitude-earthquake-rocks-buildings-in-anchorage/

54. Balbus, J., A. Crimmins, J.L. Gamble, D.R. Easterling, K.E. Kunkel, S. Saha, and M.C. Sarofim, 2016: Ch. 1. Introduction: Climate change and human health. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 25–42. https://doi.org/10.7930/j0vx0dfw

55. Cochran, P., O.H. Huntington, C. Pungowiyi, S. Tom, F.S. Chapin, III, H.P. Huntington, N.G. Maynard, and S.F. Trainor, 2013: Indigenous frameworks for observing and responding to climate change in Alaska. *Climatic Change*, **120** (3), 557–567. https://doi.org/10.1007/s10584-013-0735-2

56. Sohns, A., J.D. Ford, J. Adamowski, and B.E. Robinson, 2021: Participatory modeling of water vulnerability in remote Alaskan households using causal loop diagrams. *Environmental Management*, **67** (1), 26–42. https://doi.org/10.1007/s00267-020-01387-1

57. Yoder, S., 2018: Assessment of the potential health impacts of climate change in Alaska. *State of Alaska Epidemiology Bulletin*, **20** (1). https://arctichealth.org/en/permalink/ahliterature287905

58. Driscoll, D.L., E. Mitchell, R. Barker, J.M. Johnston, and S. Renes, 2016: Assessing the health effects of climate change in Alaska with community-based surveillance. *Climatic Change*, **137** (3), 455–466. https://doi.org/10.1007/s10584-016-1687-0

59. Eichelberger, L.P., 2010: Living in utility scarcity: Energy and water insecurity in northwest Alaska. *American Journal of Public Health*, **100** (6), 1010–1018. https://doi.org/10.2105/ajph.2009.160846

60. Thomas, T.K., T. Ritter, D. Bruden, M. Bruce, K. Byrd, R. Goldberger, J. Dobson, K. Hickel, J. Smith, and T. Hennessy, 2015: Impact of providing in-home water service on the rates of infectious diseases: Results from four communities in Western Alaska. *Journal of Water and Health*, **14** (1), 132–141. https://doi.org/10.2166/wh.2015.110

61. OCCHE, 2022: Climate Change and Health Equity. U.S. Department of Health and Human Services, Office of Climate Change and Health Equity. https://www.hhs.gov/climate-change-health-equity-environmental-justice/climate-change-health-equity/index.html

62. Eichelberger, L., S. Dev, T. Howe, D.L. Barnes, E. Bortz, B.R. Briggs, P. Cochran, A.D. Dotson, D.M. Drown, M.B. Hahn, K. Mattos, and S. Aggarwal, 2021: Implications of inadequate water and sanitation infrastructure for community spread of COVID-19 in remote Alaskan communities. *Science of The Total Environment*, **776**, 145842. https://doi.org/10.1016/j.scitotenv.2021.145842

63. Rodriguez-Lonebear, D., N.E. Barceló, R. Akee, and S.R. Carroll, 2020: American Indian reservations and COVID-19: Correlates of early infection rates in the pandemic. *Journal of Public Health Management and Practice*, **26** (4), 371–377. https://doi.org/10.1097/phh.0000000000001206

64. Wong, M.S., D.M. Upchurch, W.N. Steers, T.P. Haderlein, A.T. Yuan, and D.L. Washington, 2022: The role of community-level factors on disparities in COVID-19 infection among American Indian/Alaska Native veterans. *Journal of Racial and Ethnic Health Disparities*, **9** (5), 1861–1872. https://doi.org/10.1007/s40615-021-01123-3

65. ADEC, 2013: Alaska Water and Sewer Challenge. Alaska Department of Environmental Conservation. http://watersewerchallenge.alaska.gov/

66. ANTHC, 2019: Portable Alternative Sanitation System Connects In-Home Sanitation Systems Where It Was Impossible Before. Alaska Native Tribal Health Consortium. https://www.anthc.org/news/portable-alternative-sanitation-system-connects-in-home-sanitation-systems-where-it-was-impossible-before/

67. Hennessy, T.W., T. Ritter, R.C. Holman, D.L. Bruden, K.L. Yorita, L. Bulkow, J.E. Cheek, R.J. Singleton, and J. Smith, 2008: The relationship between in-home water service and the risk of respiratory tract, skin, and gastrointestinal tract infections among rural Alaska natives. *American Journal of Public Health*, **98** (11), 2072–2078. https://doi.org/10.2105/ajph.2007.115618

68. Hicks, K.L., S.K. Robler, A. Platt, S.N. Morton, J.R. Egger, and S.D. Emmett, 2023: Environmental factors for hearing loss and middle ear disease in Alaska Native children and adolescents: A cross-sectional analysis from a cluster randomized trial. *Ear and Hearing*, **44** (1), 2–9. https://doi.org/10.1097/aud.0000000000001265

69. Mosites, E., B. Lefferts, S. Seeman, G. January, J. Dobson, D. Fuente, M. Bruce, T. Thomas, and T. Hennessy, 2020: Community water service and incidence of respiratory, skin, and gastrointestinal infections in rural Alaska, 2013–2015. *International Journal of Hygiene and Environmental Health*, **225**, 113475. https://doi.org/10.1016/j.ijheh.2020.113475

70. Brock, R.L., M.W. O'Hara, K.J. Hart, J.E. McCabe-Beane, J.A. Williamson, A. Brunet, D.P. Laplante, C. Yu, and S. King, 2015: Peritraumatic distress mediates the effect of severity of disaster exposure on perinatal depression: The Iowa flood study. *Journal of Traumatic Stress*, **28** (6), 515–522. https://doi.org/10.1002/jts.22056

71. Mallett, L.H. and R.A. Etzel, 2018: Flooding: What is the impact on pregnancy and child health? *Disasters*, **42** (3), 432–458. https://doi.org/10.1111/disa.12256

72. Thoman, R., 2022: Typhoon Merbok, fueled by unusually warm Pacific Ocean, pounded Alaska's vulnerable coastal communities at a critical time. *The Conversation*. https://theconversation.com/typhoon-merbok-fueled-by-unusually-warm-pacific-ocean-pounded-alaskas-vulnerable-coastal-communities-at-a-critical-time-190898

73. Cunsolo, A. and N.R. Ellis, 2018: Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, **8** (4), 275–281. https://doi.org/10.1038/s41558-018-0092-2

74. Cianconi, P., S. Betrò, and L. Janiri, 2020: The impact of climate change on mental health: A systematic descriptive review. *Frontiers in Psychiatry*, **11**, 74. https://doi.org/10.3389/fpsyt.2020.00074

75. Donkersloot, R., J.C. Black, C. Carothers, D. Ringer, W. Justin, P.M. Clay, M.R. Poe, E.R. Gavenus, W. Voinot-Baron, C. Stevens, M. Williams, J. Raymond-Yakoubian, F. Christiansen, S.J. Breslow, S.J. Langdon, J.M. Coleman, and S.J. Clark, 2020: Assessing the sustainability and equity of Alaska salmon fisheries through a well-being framework. *Ecology and Society*, **25** (2). https://doi.org/10.5751/es-11549-250218

76. Oscarville Traditional Village, 2019: Pektayiinata = We Are Resilient: Oscarville Tribal Climate Adaptation Plan. U.S. Department of Interior, Bureau of Indian Affairs, Tribal Resilience Program, Oscarville, AK. https://www.nna-co.org/index.php/resource/oscarville-tribal-climate-adaptation-plan

77. Dannenberg, A.L., H. Frumkin, J.J. Hess, and K.L. Ebi, 2019: Managed retreat as a strategy for climate change adaptation in small communities: Public health implications. *Climatic Change*, **153** (1), 1–14. https://doi.org/10.1007/s10584-019-02382-0

78. Knodel, M., 2014: Conceptualizing climate justice in Kivalina. *Seattle University Law Review*, **37** (4). https://digitalcommons.law.seattleu.edu/sulr/vol37/iss4/4

79. Trombley, J., S. Chalupka, and L. Anderko, 2017: Climate change and mental health. *AJN The American Journal of Nursing*, **117** (4), 44–52. https://doi.org/10.1097/01.naj.0000515232.51795.fa

80. Allen, J., L. Wexler, and S. Rasmus, 2022: Protective factors as a unifying framework for strength-based intervention and culturally responsive American Indian and Alaska Native suicide prevention. *Prevention Science*, **23** (1), 59–72. https://doi.org/10.1007/s11121-021-01265-0

81. Cunsolo Willox, A., E. Stephenson, J. Allen, F. Bourque, A. Drossos, S. Elgarøy, M.J. Kral, I. Mauro, J. Moses, T. Pearce, J.P. MacDonald, and L. Wexler, 2015: Examining relationships between climate change and mental health in the circumpolar North. *Regional Environmental Change*, **15** (1), 169–182. https://doi.org/10.1007/s10113-014-0630-z

82. Hahn, M.B., G. Kuiper, K. O'Dell, E.V. Fischer, and S. Magzamen, 2021: Wildfire smoke is associated with an increased risk of cardiorespiratory emergency department visits in Alaska. *GeoHealth*, **5** (5), e2020GH000349. https://doi.org/10.1029/2020gh000349

83. Hahn, M.B., G. Disler, L.A. Durden, S. Coburn, F. Witmer, W. George, K. Beckmen, and R. Gerlach, 2020: Establishing a baseline for tick surveillance in Alaska: Tick collection records from 1909–2019. *Ticks and Tick-borne Diseases*, **11** (5), 101495. https://doi.org/10.1016/j.ttbdis.2020.101495

84. Witmer, F.D.W., T.W. Nawrocki, and M. Hahn, 2022: Modeling geographic uncertainty in current and future habitat for potential populations of *Ixodes pacificus* (Acari: Ixodidae) in Alaska. *Journal of Medical Entomology*, **59** (3), 976–986. https://doi.org/10.1093/jme/tjac001

85. Beckmen, K., 2021: Rabies outbreak in western Alaska sparks team response. *Alaska Fish and Wildlife News*, June 2021. https://www.adfg.alaska.gov/index.cfm?adfg=wildlifenews.view_article&articles_id=993

86. Kim, B.I., J.D. Blanton, A. Gilbert, L. Castrodale, K. Hueffer, D. Slate, and C.E. Rupprecht, 2014: A conceptual model for the impact of climate change on fox rabies in Alaska, 1980–2010. *Zoonoses and Public Health*, **61** (1), 72–80. https://doi.org/10.1111/zph.12044

87. Huntington, H.P., J. Raymond-Yakoubian, G. Noongwook, N. Naylor, C. Harris, Q. Harcharek, and B. Adams, 2021: "We never get stuck:" A collaborative analysis of change and coastal community subsistence practices in the Northern Bering and Chukchi Seas, Alaska. *Arctic*, **74** (2), 113–126. https://doi.org/10.14430/arctic72446

88. Christie, K.S., T.E. Hollmen, H.P. Huntington, and J.R. Lovvorn, 2018: Structured decision analysis informed by traditional ecological knowledge as a tool to strengthen subsistence systems in a changing Arctic. *Ecology and Society*, **23** (4), 42. https://doi.org/10.5751/es-10596-230442

89. Hendrix, A.M., K.A. Lefebvre, L. Quakenbush, A. Bryan, R. Stimmelmayr, G. Sheffield, G. Wisswaesser, M.L. Willis, E.K. Bowers, P. Kendrick, E. Frame, T. Burbacher, and D.J. Marcinek, 2021: Ice seals as sentinels for algal toxin presence in the Pacific Arctic and subarctic marine ecosystems. *Marine Mammal Science*, **37** (4), 1292–1308. https://doi.org/10.1111/mms.12822

90. Lefebvre, K.A., L. Quakenbush, E. Frame, K. Burek, G. Sheffield, R. Stimmelmayr, A. Bryan, P. Kendrick, H. Ziel, T. Goldstein, J.A. Snyder, T. Gelatt, F. Gulland, B. Dickerson, and V. Gill, 2016: Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. *Harmful Algae*, **55**, 13–24. https://doi.org/10.1016/j.hal.2016.01.007

91. Van Hemert, C., J.D. Robert, M.S. Matthew, K. Robert, S. Gay, M.D. Lauren, J.K. Kathy, K. Susan, S.L. Julia, D.R. Hardison, R.W. Litaker, J. Timothy, K.B. Hillary, and K.P. Julia, 2021: Investigation of algal toxins in a multispecies seabird die-off in the Bering and Chukchi seas. *Journal of Wildlife Diseases*, **57** (2), 399–407. https://doi.org/10.7589/jwd-d-20-00057

92. Van Hemert, C., S.K. Schoen, R.W. Litaker, M.M. Smith, M.L. Arimitsu, J.F. Piatt, W.C. Holland, D. Ransom Hardison, and J.M. Pearce, 2020: Algal toxins in Alaskan seabirds: Evaluating the role of saxitoxin and domoic acid in a large-scale die-off of common murres. *Harmful Algae*, **92**, 101730. https://doi.org/10.1016/j.hal.2019.101730

93. Johnson-Agbakwu, C.E., N.S. Ali, C.M. Oxford, S. Wingo, E. Manin, and D.V. Coonrod, 2022: Racism, COVID-19, and health inequity in the USA: A call to action. *Journal of Racial and Ethnic Health Disparities*, **9** (1), 52–58. https://doi.org/10.1007/s40615-020-00928-y

94. van Dorn, A., R.E. Cooney, and M.L. Sabin, 2020: COVID-19 exacerbating inequalities in the US. *The Lancet*, **395** (10232), 1243–1244. https://doi.org/10.1016/s0140-6736(20)30893-x

95. Cana Uluaq Itchuaqiyaq (Author), May 13, 2022: Email communication with Gladys I'yiiqpak Pungowiyi (Iñupiaq), Kotzebue, Alaska.

96. ADLWD, 2020: Alaska Population Overview: 2019 Estimates. Alaska Department of Labor and Workforce Development, Research and Analysis Section. https://live.laborstats.alaska.gov/pop/estimates/pub/19popover.pdf

97. Berman, M. and J.I. Schmidt, 2019: Economic effects of climate change in Alaska. *Weather, Climate, and Society*, **11** (2), 245–258. https://doi.org/10.1175/wcas-d-18-0056.1

98. NTIA, 2020: Indicators of Broadband Need Map. U.S. Department of Commerce, National Telecommunications and Information Administration. https://broadbandusa.ntia.doc.gov/resources/data-and-mapping

99. Tracie Curry (Author), March 10, 2023: Telephone and email communication with Thomas Lochner, director of the Alaska broadband office, Alaska Department of Commerce, Community, and Economic Development.

100. Hudson, H.E., V. Hanna, A. Hill, K. Parker, S. Sharp, K. Spiers, and K. Wark, 2021: Toward Universal Broadband in Rural Alaska: Final Report. State of Alaska, Governor's Task Force on Broadband. https://indd.adobe.com/view/42ddcfe3-5ea9-4bcb-bd09-a71bcb63869a

101. FNSB, 2021: Geographic Information Services (GIS). Fairbanks North Star Borough. https://fnsb.gov/433/geographic-information-services-gis

102. NRCS, 2019: Web Soil Survey. U.S. Department of Agriculture, Natural Resources Conservation Service. https://websoilsurvey.nrcs.usda.gov/app/

103. U.S. Census Bureau, 2021: American Community Survey (ACS). U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/programs-surveys/acs

104. Hartman, I.C., 2020: *Black History in the Last Frontier*. Johnson, K., Ed. National Park Service. https://www.nps.gov/articles/upload/black-history-in-the-last-frontier_reader_compressed.pdf

105. ADLWD, 2021: 2021 Population Estimates by Borough, Census Area, and Economic Region. Alaska Department of Labor and Workforce Development, Juneau, AK. https://live.laborstats.alaska.gov/pop/index.cfm

106. State of Alaska, 2022: Administrative Order No. 331: Alaska Food Security and Independence Task Force. State of Alaska, Office of the Governor. https://gov.alaska.gov/admin-orders/administrative-order-no-331/

107. Fried, N., 2019: The Cost of Living: 2018 and Early 2019. State of Alaska, Department of Labor and Workforce Development. https://live.laborstats.alaska.gov/trends-articles/2019/07/the-cost-of-living-in-alaska

108. SNAP, 2022: State Activity Report: Fiscal Year 2020. Food and Nutrition Service, Supplemental Nutrition Assistance Program. https://www.fns.usda.gov/pd/snap-state-activity-reports

109. Fall, J.A., 2018: Subsistence in Alaska: A Year 2017 Update. Alaska Department of Fish and Game, Division of Subsistence, Anchorage, AK, 4 pp. http://www.adfg.alaska.gov/static/home/subsistence/pdfs/subsistence_update_2017.pdf

110. Cheng, M., M. Zhang, R.M. Van Veldhuizen, and C.W. Knight, 2021: Growing season and phenological stages of small grain crops in response to climate change in Alaska. *American Journal of Climate Change*, **10** (4), 490–511. https://doi.org/10.4236/ajcc.2021.104025

111. Fresco, N., A. Bennett, P. Bieniek, and C. Rosner, 2021: Climate change, farming, and gardening in Alaska: Cultivating opportunities. *Sustainability*, **13** (22), 12713. https://doi.org/10.3390/su132212713

112. Lader, R., J.E. Walsh, U.S. Bhatt, and P.A. Bieniek, 2018: Agro-climate projections for a warming Alaska. *Earth Interactions*, **22** (18), 1–24. https://doi.org/10.1175/ei-d-17-0036.1

113. Clifford, L., 2022: North Pole man killed in head-on collision on the Richardson Highway. *Fairbanks Daily News-Miner*, March 2, 2022. https://www.newsminer.com/news/alaska_news/north-pole-man-killed-in-head-on-collision-on-the-richardson-highway/article_f25008e0-9a9b-11ec-bfef-6f7855147b3b.html

114. Williams, T., 2021: Interior Alaska storm wreaks havoc as highways temporarily close and thousands remain without power. *Anchorage Daily News*, December 27, 2021. https://www.adn.com/alaska-news/weather/2021/12/27/interior-alaska-storm-wreaks-havoc-as-highways-temporarily-close-and-thousands-remain-without-power/

115. Kitchenman, A., 2022: Gov. Dunleavy issues disaster declaration for Interior Alaska and Mat-Su storms. *KTOO Public Media*, January 3, 2022. https://www.ktoo.org/2022/01/03/dunleavy-disaster-declaration-alaska-storms/

116. The White House, 2022: President Joseph R. Biden, Jr. Approves Alaska Disaster Declaration. The White House. https://www.whitehouse.gov/briefing-room/statements-releases/2022/03/24/president-joseph-r-biden-jr-approves-alaska-disaster-declaration-4/

117. Alyssa Quintyne (Author), May 4, 2022: Email communication with Marjorie Casort, Fairbanks, Alaska.

118. Watson, E., 2022: I hope people talk about this storm for a long time. *Anchorage Daily News*, January 4, 2022. https://www.adn.com/opinions/2022/01/04/i-hope-people-talk-about-this-storm-for-a-long-time/

119. AMAP, 2021: Arctic Climate Change Update 2021: Key Trends and Impacts. Arctic Monitoring and Assessment Programme, Tromsø, Norway. https://www.amap.no/documents/download/6759/inline

120. NASS, 2019: Census of Agriculture: 2017 State and Area Profiles—Alaska. U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/publications/agcensus/2017/online_resources/county_profiles/alaska/index.php

121. McDowell Group, 2018: Economic Impact of Alaska's Visitor Industry 2017. State of Alaska, Department of Commerce, Community, and Economic Development. https://www.mcdowellgroup.net/wp-content/uploads/2018/11/visitor-impacts-2016-17-report.pdf

122. McKinley Research Group, 2022: The Economic Value of Alaska's Seafood Industry. The Alaska Seafood Marketing Institute. https://www.alaskaseafood.org/wp-content/uploads/MRG_ASMI-Economic-Impacts-Report_final.pdf

123. Barbeaux, S.J., K. Holsman, and S. Zador, 2020: Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific cod fishery. *Frontiers in Marine Science*, **7**, 703. https://doi.org/10.3389/fmars.2020.00703

124. Conrad, S. and D. Gray, 2018: Overview of the 2017 Southeast Alaska and Yakutat Commercial, Personal Use, and Subsistence Salmon Fisheries. Fishery Management Report No. 18-01. Alaska Department of Fish and Game, Division of Sport Fish, Research and Technical Services, Anchorage, AK. https://www.adfg.alaska.gov/fedaidpdfs/fmr18-01.pdf

125. Garber-Yonts, B. and J. Lee, 2020: Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands Area: Economic Status of the BSAI King and Tanner Crab Fisheries off Alaska, 2019. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Seattle, WA. https://repository.library.noaa.gov/view/noaa/23002

126. Oke, K.B., C.J. Cunningham, P.A.H. Westley, M.L. Baskett, S.M. Carlson, J. Clark, A.P. Hendry, V.A. Karatayev, N.W. Kendall, J. Kibele, H.K. Kindsvater, K.M. Kobayashi, B. Lewis, S. Munch, J.D. Reynolds, G.K. Vick, and E.P. Palkovacs, 2020: Recent declines in salmon body size impact ecosystems and fisheries. *Nature Communications*, **11** (1), 1–13. https://doi.org/10.1038/s41467-020-17726-z

127. NMFS, 2022: Fisheries of the United States, 2020. NOAA Current Fishery Statistics No. 2020. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2020

128. Alaska Department of Fish and Game, 2021: 2021 Upper Cook Inlet Commercial Salmon Fishery Season Summary. Alaska Department of Fish and Game, Division of Commercial Fisheries, 15 pp. https://www.adfg.alaska.gov/static/applications/dcfnewsrelease/1346668657.pdf

129. Barbeaux, S., K. Aydin, B. Fissel, K. Holsman, W. Palsson, K. Shotwell, Q. Yang, and S. Zador, 2017: Assessment of the Pacific cod stock in the Gulf of Alaska. In: *NPFMC Gulf of Alaska SAFE*. North Pacific Fishery Management Council, 183–326. https://repository.library.noaa.gov/view/noaa/17515

130. Dorn, M., K. Aydin, B. Fissel, W. Palsson, K. Spalinger, S. Stienessen, K. Williams, and S. Zador, 2018: Ch. 1. Assessment of the walleye pollock stock in the Gulf of Alaska. In: *NPFMC Gulf of Alaska SAFE*. North Pacific Fishery Management Council, 130. https://apps-afsc.fisheries.noaa.gov/refm/docs/2018/goa/goapollock.pdf

131. Szuwalski, C., W. Cheng, R. Foy, A.J. Hermann, A. Hollowed, K. Holsman, J. Lee, W. Stockhausen, and J. Zheng, 2021: Climate change and the future productivity and distribution of crab in the Bering Sea. *ICES Journal of Marine Science*, **78** (2), 502–515. https://doi.org/10.1093/icesjms/fsaa140

132. MacArthur, A.R., 2022: Federal disasters declared for 14 Alaska fisheries. *Alaska Public Media*, January 25, 2022. https://alaskapublic.org/2022/01/25/federal-disasters-declared-for-kuskokwim-and-yukon-salmon-fisheries/

133. NCEI, 2022: Climate at a Glance: Global Mapping. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/global

134. Hunt, G.L., L. Eisner, and N.M. Call, 2021: How will diminishing sea ice impact commercial fishing in the Bering Sea? *Arctic, Antarctic, and Alpine Research*, **53** (1), 269–270. https://doi.org/10.1080/15230430.2021.1974668

135. Hurst, T.P., L.A. Copeman, S.A. Haines, S.D. Meredith, K. Daniels, and K.M. Hubbard, 2019: Elevated $CO_2$ alters behavior, growth, and lipid composition of Pacific cod larvae. *Marine Environmental Research*, **145**, 52–65. https://doi.org/10.1016/j.marenvres.2019.02.004

136. Rogers, L.A., M.T. Wilson, J.T. Duffy-Anderson, D.G. Kimmel, and J.F. Lamb, 2021: Pollock and "the blob": Impacts of a marine heatwave on walleye pollock early life stages. *Fisheries Oceanography*, **30** (2), 142–158. https://doi.org/10.1111/fog.12508

137. Carey, M.P., V.R. von Biela, A. Dunker, K.D. Keith, M. Schelske, C. Lean, and C.E. Zimmerman, 2021: Egg retention of high-latitude sockeye salmon (*Oncorhynchus nerka*) in the Pilgrim River, Alaska, during the Pacific marine heatwave of 2014–2016. *Polar Biology*, **44** (8), 1643–1654. https://doi.org/10.1007/s00300-021-02902-8

138. Shanley, C.S., S. Pyare, M.I. Goldstein, P.B. Alaback, D.M. Albert, C.M. Beier, T.J. Brinkman, R.T. Edwards, E. Hood, A. MacKinnon, M.V. McPhee, T.M. Patterson, L.H. Suring, D.A. Tallmon, and M.S. Wipfli, 2015: Climate change implications in the northern coastal temperate rainforest of North America. *Climatic Change*, **130** (2), 155–170. https://doi.org/10.1007/s10584-015-1355-9

139. von Biela, V.R., L. Bowen, S.D. McCormick, M.P. Carey, D.S. Donnelly, S. Waters, A.M. Regish, S.M. Laske, R.J. Brown, S. Larson, S. Zuray, and C.E. Zimmerman, 2020: Evidence of prevalent heat stress in Yukon River Chinook salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, **77** (12), 1878–1892. https://doi.org/10.1139/cjfas-2020-0209

140. Williams, C.R., A.H. Dittman, P. McElhany, D.S. Busch, M.T. Maher, T.K. Bammler, J.W. MacDonald, and E.P. Gallagher, 2019: Elevated $CO_2$ impairs olfactory-mediated neural and behavioral responses and gene expression in ocean-phase coho salmon (*Oncorhynchus kisutch*). *Global Change Biology*, **25** (3), 963–977. https://doi.org/10.1111/gcb.14532

141. Dickinson, G.H., S. Bejerano, T. Salvador, C. Makdisi, S. Patel, W.C. Long, K.M. Swiney, R.J. Foy, B.V. Steffel, K.E. Smith, and R.B. Aronson, 2021: Ocean acidification alters properties of the exoskeleton in adult Tanner crabs, *Chionoecetes bairdi*. *Journal of Experimental Biology*, **224** (3), 232819. https://doi.org/10.1242/jeb.232819

142. Alabia, I.D., J. García Molinos, S.I. Saitoh, T. Hirawake, T. Hirata, and F.J. Mueter, 2018: Distribution shifts of marine taxa in the Pacific Arctic under contemporary climate changes. *Diversity and Distributions*, **24** (11), 1583–1597. https://doi.org/10.1111/ddi.12788

143. Huntington, H.P., S.L. Danielson, F.K. Wiese, M. Baker, P. Boveng, J.J. Citta, A. De Robertis, D.M.S. Dickson, E. Farley, J.C. George, K. Iken, D.G. Kimmel, K. Kuletz, C. Ladd, R. Levine, L. Quakenbush, P. Stabeno, K.M. Stafford, D. Stockwell, and C. Wilson, 2020: Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, **10** (4), 342–348. https://doi.org/10.1038/s41558-020-0695-2

144. Rogers, L.A. and A.B. Dougherty, 2019: Effects of climate and demography on reproductive phenology of a harvested marine fish population. *Global Change Biology*, **25** (2), 708–720. https://doi.org/10.1111/gcb.14483

145. Kovach, R.P., S.C. Ellison, S. Pyare, and D.A. Tallmon, 2015: Temporal patterns in adult salmon migration timing across southeast Alaska. *Global Change Biology*, **21** (5), 1821–1833. https://doi.org/10.1111/gcb.12829

146. Dorn, M.W., A.L. Deary, B.E. Fissel, D.T. Jones, M. Levine, A.L. McCarthy, W.A. Palsson, L.A. Rogers, S.K. Shotwell, K.A. Spalinger, K. Williams, and S.G. Zador, 2020: Ch. 1. Assessment of the walleye pollock stock in the Gulf of Alaska. In: *NPFMC Gulf of Alaska SAFE*. North Pacific Fishery Management Council, 135. https://apps-afsc.fisheries.noaa.gov/refm/docs/2020/goapollock.pdf

147. Nichol, D.G., S. Kotwicki, T.K. Wilderbuer, R.R. Lauth, and J.N. Ianelli, 2019: Availability of yellowfin sole *Limanda aspera* to the eastern Bering Sea trawl survey and its effect on estimates of survey biomass. *Fisheries Research*, **211**, 319–330. https://doi.org/10.1016/j.fishres.2018.11.017

148. Logerwell, E.A., M. Wang, L.L. Jörgensen, and K. Rand, 2022: Winners and losers in a warming Arctic: Potential habitat gain and loss for epibenthic invertebrates of the Chukchi and Bering Seas, 2008–2100. *Deep Sea Research Part II: Topical Studies in Oceanography*, **206**, 105210. https://doi.org/10.1016/j.dsr2.2022.105210

149. Rooper, C.N., I. Ortiz, A.J. Hermann, N. Laman, W. Cheng, K. Kearney, and K. Aydin, 2021: Predicted shifts of groundfish distribution in the eastern Bering Sea under climate change, with implications for fish populations and fisheries management. *ICES Journal of Marine Science*, **78** (1), 220–234. https://doi.org/10.1093/icesjms/fsaa215

150. Huntington, H.P., A. Begossi, S.F. Gearheard, B. Kersey, P.A. Loring, T. Mustonen, P.K. Paudel, R.A.M. Silvano, and R. Vave, 2017: How small communities respond to environmental change: Patterns from tropical to polar ecosystems. *Ecology and Society*, **22** (3), 9. https://doi.org/10.5751/es-09171-220309

151. Kasperski, S. and D.S. Holland, 2013: Income diversification and risk for fishermen. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (6), 2076–2081. https://doi.org/10.1073/pnas.1212278110

152. Halofsky, J.E., J.S. Littell, D.L. Peterson, G.D. Hayward, and R. Gravenmier, 2019: Ch. 3. Managing effects of drought and other water resource challenges in Alaska and the Pacific Northwest. In: *Effects of Drought on Forests and Rangelands in the United States: Translating Science Into Management Responses*. Vose, J.M., D.L. Peterson, C.H. Luce, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 41–69. https://www.fs.usda.gov/research/treesearch/59162

153. Hasbrouck, T.R., T.J. Brinkman, G. Stout, E. Trochim, and K. Kielland, 2020: Quantifying effects of environmental factors on moose harvest in Interior Alaska. *Wildlife Biology*, **2020** (2). https://doi.org/10.2981/wlb.00631

154. Green, K.M., A.H. Beaudreau, M.H. Lukin, and L.B. Crowder, 2021: Climate change stressors and social-ecological factors mediating access to subsistence resources in Arctic Alaska. *Ecology and Society*, **26** (4). https://doi.org/10.5751/es-12783-260415

155. Huntington, H.P., L.T. Quakenbush, and M. Nelson, 2017: Evaluating the effects of climate change on indigenous marine mammal hunting in northern and western Alaska using traditional knowledge. *Frontiers in Marine Science*, **4**, 319. https://doi.org/10.3389/fmars.2017.00319

156. Bieniek, P.A., U.S. Bhatt, J.E. Walsh, R. Lader, B. Griffith, J.K. Roach, and R.L. Thoman, 2018: Assessment of Alaska rain-on-snow events using dynamical downscaling. *Journal of Applied Meteorology and Climatology*, **57** (8), 1847–1863. https://doi.org/10.1175/jamc-d-17-0276.1

157. Joly, K., A. Gunn, S.D. Côté, M. Panzacchi, J. Adamczewski, M.J. Suitor, and E. Gurarie, 2021: Caribou and reindeer migrations in the changing Arctic. *Animal Migration*, **8** (1), 156–167. https://doi.org/10.1515/ami-2020-0110

158. Mulder, C.P.H., K.V. Spellman, and J. Shaw, 2021: Berries in winter: A natural history of fruit retention in four species across Alaska. *Madroño*, **68** (4), 487–510. https://doi.org/10.3120/0024-9637-68.4.487

159. Hupp, J., M. Brubaker, K. Wilkinson, and J. Williamson, 2015: How are your berries? Perspectives of Alaska's environmental managers on trends in wild berry abundance. *International Journal of Circumpolar Health*, **74** (1), 28704. https://doi.org/10.3402/ijch.v74.28704

160. Herman-Mercer, N.M., R.A. Loehman, R.C. Toohey, and C. Paniyak, 2020: Climate- and disturbance-driven changes in subsistence berries in coastal Alaska: Indigenous Knowledge to inform ecological inference. *Human Ecology*, **48** (1), 85–99. https://doi.org/10.1007/s10745-020-00138-4

161. Alaska Native Renewable Industries, 2022: Alaska Native Renewable Industries [Webpage], accessed April 3, 2023. https://anr-industries.com/

162. Goddard, E., 2023: Solar Professionals Installation Training. University of Alaska Fairbanks, Bristol Bay Campus, accessed April 3, 2023. https://uaf.edu/bbc/academics/sustainable-energy/solarprofessionalstraining.php

163. Alutiiq Pride Marine Institute, 2021: Welcome to the Alutiiq Pride Marine Institute [Website], accessed April 3, 2023. https://www.alutiiqprideak.org/

164. Calypso Farm and Ecology Center, 2022: Calypso Farm & Ecology Center [Website]. https://calypsofarm.org/

165. City of Fairbanks, 2022: Mobile Crisis Team. City of Fairbanks, Alaska. https://www.fairbanksalaska.us/crisis/page/mobile-crisis-team-call-911-access-mobile-crisis-team

166. Ross, I., 2021: As low Chignik salmon runs continue, people worry their communities will disappear. *KTOO Public Media*, September 13, 2021. https://www.ktoo.org/2021/09/13/as-low-chignik-salmon-runs-continue-people-worry-their-communities-will-disappear/

167. Fang, Z., P.T. Freeman, C.B. Field, and K.J. Mach, 2018: Reduced sea ice protection period increases storm exposure in Kivalina, Alaska. *Arctic Science*, **4** (4), 525–537. https://doi.org/10.1139/as-2017-0024

168. Gibbs, A.E., A. Ohman. Karen, and B.M. Richmond, 2015: National Assessment of Shoreline Change: A GIS Compilation of Vector Shorelines and Associated Shoreline Change Data for the North Coast of Alaska, U.S.-Canadian Border to Icy Cape. USGS Open-File Report 2015-1030. U.S. Geological Survey, Reston, VA. https://doi.org/10.3133/ofr20151030

169. Irrgang, A.M., M. Bendixen, L.M. Farquharson, A.V. Baranskaya, L.H. Erikson, A.E. Gibbs, S.A. Ogorodov, P.P. Overduin, H. Lantuit, M.N. Grigoriev, and B.M. Jones, 2022: Drivers, dynamics and impacts of changing Arctic coasts. *Nature Reviews Earth & Environment*, **3** (1), 39–54. https://doi.org/10.1038/s43017-021-00232-1

170. Melvin, A.M., P. Larsen, B. Boehlert, J.E. Neumann, P. Chinowsky, X. Espinet, J. Martinich, M.S. Baumann, L. Rennels, A. Bothner, D.J. Nicolsky, and S.S. Marchenko, 2017: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (2), E122–E131. https://doi.org/10.1073/pnas.1611056113

171. UAFINE, 2019: Statewide Threat Assessment: Identification of Threats from Erosion, Flooding, and Thawing Permafrost in Remote Alaska Communities. Report #INE 19.03. University of Alaska Fairbanks, Institute of Northern Engineering. https://www.denali.gov/wp-content/uploads/2019/11/Statewide-Threat-Assessment-Final-Report-20-November-2019.pdf

172. Gorokhovich, Y. and A. Leiserowiz, 2012: Historical and future coastal changes in Northwest Alaska. *Journal of Coastal Research*, **28** (1A), 174–186. https://doi.org/10.2112/jcoastres-d-11-00031.1

173. Overbeck, J.R., R.M. Buzard, M.M. Turner, K.Y. Miller, and R.J. Glenn, 2020: Shoreline Change at Alaska Coastal Communities. Report of Investigation 2020-10. Alaska Division of Geological and Geophysical Surveys, 29 pp. https://doi.org/10.14509/30552

174. Jorgenson, M.T., G.V. Frost, and D. Dissing, 2018: Drivers of landscape changes in coastal ecosystems on the Yukon-Kuskokwim Delta, Alaska. *Remote Sensing*, **10** (8), 1280. https://doi.org/10.3390/rs10081280

175. Jorgenson, T., K. Yoshikawa, M. Kanevskiy, Y. Shur, V. Romanovsky, S. Marchenko, G. Grosse, J. Brown, and B. Jones, 2008: Permafrost characteristics of Alaska. In: *Proceedings of the Ninth International Conference on Permafrost*. Kane, D.L. and K.M. Hinkel, Eds. Institute of Northern Engineering, University of Alaska Fairbanks, Fairbanks, AK. https://permafrost.gi.alaska.edu/sites/default/files/AlaskaPermafrostMap_Back_Jun2008_Jorgenson_etal_2008.pdf

176. Streletskiy, D.A., S. Clemens, J.-P. Lanckman, and N.I. Shiklomanov, 2023: The costs of Arctic infrastructure damages due to permafrost degradation. *Environmental Research Letters*, **18** (1), 015006. https://doi.org/10.1088/1748-9326/acab18

177. Bull, D.L., E.M. Bristol, E. Brown, R.C. Choens, C.T. Connolly, C. Flanary, J.M. Frederick, B.M. Jones, C.A. Jones, M. Ward Jones, J.W. McClelland, A. Mota, and I.K. Tezaur, 2020: Arctic Coastal Erosion: Modeling and Experimentation. U.S. Department of Energy, Office of Scientific and Technical Information. https://doi.org/10.2172/1670531

178. Buzard, R.M., M.M. Turner, K.Y. Miller, D.C. Antrobus, and J.R. Overbeck, 2021: Erosion Exposure Assessment of Infrastructure in Alaska Coastal Communities. DGGS RI 2021-3. Alaska Division of Geological and Geophysical Surveys, 29 pp. https://doi.org/10.14509/30672

179. Chiskok, D., 2019: Erosion of Russian Era Graves. LEO Network. https://www.leonetwork.org/en/posts/show/db77d295-6d87-4741-9c93-d626c8a38108

180. Seetook, D., M. Brubaker, and M. Neale, 2019: Erosion Threatening Burial Site. LEO Network. https://www.leonetwork.org/en/posts/show/0aaffcaf-13b0-4017-80b6-7e628d7ca21e

181. BIA, 2020: The Unmet Infrastructure Needs of Tribal Communities and Alaska Native Villages in Process of Relocating to Higher Ground as a Result of Climate Change. Department of Interior, Bureau of Indian Affairs, Albuquerque, NM. https://www.bia.gov/news/unmet-infrastructure-needs-tribal-communities-and-alaska-native-villages-process-relocation

182. Schneider von Deimling, T., H. Lee, T. Ingeman-Nielsen, S. Westermann, V. Romanovsky, S. Lamoureux, D.A. Walker, S. Chadburn, E. Trochim, L. Cai, J. Nitzbon, S. Jacobi, and M. Langer, 2021: Consequences of permafrost degradation for Arctic infrastructure—Bridging the model gap between regional and engineering scales. *Cryosphere*, **15** (5), 2451–2471. https://doi.org/10.5194/tc-15-2451-2021

183. Albert, S., R. Bronen, N. Tooler, J. Leon, D. Yee, J. Ash, D. Boseto, and A. Grinham, 2018: Heading for the hills: Climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5 °C future. *Regional Environmental Change*, **18** (8), 2261–2272. https://doi.org/10.1007/s10113-017-1256-8

184. BLM, 2020: Appendix I.2 ConocoPhillips road optimization memorandum. In: *Willow Master Development Plan*. Bureau of Land Management, U.S. Department of the Interior, 9. https://eplanning.blm.gov/eplanning-ui/project/109410/570

185. Herz, N., 2020: Big oil's answer to melting Arctic: Cooling the ground so it can keep drilling. *The Guardian*, October 19, 2020. https://www.theguardian.com/environment/2020/oct/19/oil-alaska-arctic-global-heating-local-cooling

186. Herz, N., 2021: At Denali National Park, climate change threatens the only road in and out. *Anchorage Daily News*, October 16, 2021. https://www.adn.com/alaska-news/2021/10/16/at-denali-national-park-in-alaska-climate-change-threatens-the-only-road-in-and-out/

187. NPS, 2022: Pretty Rocks Landslide. U.S. Department of Interior, National Park Service. https://www.nps.gov/dena/learn/nature/pretty-rocks.htm

188. Krakow, M., 2022: The Denali Park Road landslide made 'shocking' progress this winter, reinforcing the need for a fix. *Anchorage Daily News*, April 20, 2022. https://www.adn.com/outdoors-adventure/2022/04/20/the-denali-park-road-landslide-made-shocking-progress-this-winter-reinforcing-the-need-for-a-fix/

189. Fullman, T.J., K. Joly, and A. Ackerman, 2017: Effects of environmental features and sport hunting on caribou migration in northwestern Alaska. *Movement Ecology*, **5** (1), 4. https://doi.org/10.1186/s40462-017-0095-z

190. Dunmall, K.M., D.G. McNicholl, C.E. Zimmerman, S.E. Gilk-Baumer, S. Burril, and V.R. von Biela, 2022: First juvenile chum salmon confirms successful reproduction for Pacific salmon in the North American Arctic. *Canadian Journal of Fisheries and Aquatic Sciences*, **79** (5), 703–707. https://doi.org/10.1139/cjfas-2022-0006

191. Tape, K.D., D.D. Gustine, R.W. Ruess, L.G. Adams, and J.A. Clark, 2016: Range expansion of Moose in Arctic Alaska linked to warming and increased shrub habitat. *PLoS ONE*, **11** (4), e0152636. https://doi.org/10.1371/journal.pone.0152636

192. Tape, K.D., B.M. Jones, C.D. Arp, I. Nitze, and G. Grosse, 2018: Tundra be dammed: Beaver colonization of the Arctic. *Global Change Biology*, **24** (10), 4478–4488. https://doi.org/10.1111/gcb.14332

193. Juday, G.P., C. Alix, and T.A. Grant, 2015: Spatial coherence and change of opposite white spruce temperature sensitivities on floodplains in Alaska confirms early-stage boreal biome shift. *Forest Ecology and Management*, **350**, 46–61. https://doi.org/10.1016/j.foreco.2015.04.016

194. Cohen, J., 2019: Trumpeter Swan (*Cygnus buccinator*) Entering Breeding Grounds Early. LEO Network. https://www.leonetwork.org/en/posts/show/eaed8cdb-8b11-4972-8ad3-6bf195ed8610

195. Fischbach, A.S. and D.C. Douglas, 2022: Pacific Walrus Coastal Haulout Occurrences Interpreted from Satellite Imagery (ver. 2.0, December 2022), Data Release. U.S. Geological Survey. https://doi.org/10.5066/p9csm0kn

196. Ahtuangaruak, R., 2019: Dragon Flies Reach the Colville Nigliq Channel. LEO Network. https://www.leonetwork.org/en/posts/show/22ea9fc9-5540-4700-9de6-98f4f7599dca

197. White, R., 2019: Burying Beetle (Genus *Nicrophorus*) in Southwest Alaska. LEO Network. https://www.leonetwork.org/en/posts/show/cf977f4d-1283-4754-b145-b214f10721b8

198. USFS, 2020: Forest Health Conditions in Alaska 2020. R10-PR-46. U.S. Department of Agriculture, Forest Service, Alaska Region, Anchorage, AK, 76 pp. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd903361.pdf

199. Citta, J.J., L.T. Quakenbush, S.R. Okkonen, M.L. Druckenmiller, W. Maslowski, J. Clement-kinney, J.C. George, H. Brower, R.J. Small, C.J. Ashjian, L.A. Harwood, and M.P. Heide-Jørgensen, 2015: Ecological characteristics of core-use areas used by Bering–Chukchi–Beaufort (BCB) bowhead whales, 2006–2012. *Progress in Oceanography*, **136**, 201–222. https://doi.org/10.1016/j.pocean.2014.08.012

200. Quakenbush, L.T. and J.J. Citta, 2019: Satellite Tracking of Bowhead Whales: Habitat Use, Passive Acoustics and Environmental Monitoring. OCS Study BOEM 2019-076. U.S. Department of the Interior, Bureau of Ocean Energy Management, Alaska Outer Continental Shelf Region, Anchorage, AK. https://espis.boem.gov/final%20reports/BOEM_2019-076.pdf

201. Romano, M.D., H.M. Renner, K.J. Kuletz, J.K. Parrish, T. Jones, H.K. Burgess, D.A. Cushing, and D. Causey, 2020: Die-offs, reproductive failure, and changing at-sea abundance of murres in the Bering and Chukchi Seas in 2018. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181–182**, 104877. https://doi.org/10.1016/j.dsr2.2020.104877

202. Wiese, F.K. and R.J. Nelson, 2022: Pathways between climate, fish, fisheries, and management: A conceptual integrated ecosystem management approach. *Journal of Marine Science and Engineering*, **10** (3), 338. https://doi.org/10.3390/jmse10030338

203. Ershova, E.A., J.M. Questel, K. Kosobokova, and R.R. Hopcroft, 2017: Population structure and production of four sibling species of *Pseudocalanus* spp. in the Chukchi Sea. *Journal of Plankton Research*, **39** (1), 48–64. https://doi.org/10.1093/plankt/fbw078

204. Mordy, C.W., K. Axler, L. Copeman, A. Deary, J.T. Duffy-Anderson, L. Eisner, E. Goldstein, H. Tabisola, J.W. Krause, D. Kimmel, C. Ladd, M.W. Lomas, R.M. McCabe, J.M. Nielsen, A. Schnetzer, A. Spear, and P. Stabeno, 2022: Arctic Integrated Ecosystem Research Program Final Report for Arctic Integrated Ecosystem Survey (IES) Phase II: Oceanography and Lower Trophic Level Productivity (A92) and Microzooplankton Biomass and Grazing Rates on the Arctic Program Cruises (A70). North Pacific Research Board, Arctic Program. https://nprb-public-website.s3.us-west-2.amazonaws.com/arctic-program/A92_Arctic+IES+Oceanography+%26+Lower+Trophic+Levels.pdf

205. Copeman, L.A., C.D. Salant, M.A. Stowell, M.L. Spencer, D.G. Kimmel, A.I. Pinchuk, and B.J. Laurel, 2022: Annual and spatial variation in the condition and lipid storage of juvenile Chukchi Sea gadids during a recent period of environmental warming (2012 to 2019). *Deep Sea Research Part II: Topical Studies in Oceanography*, **205**, 105180. https://doi.org/10.1016/j.dsr2.2022.105180

206. Boveng, P.L., H.L. Ziel, B.T. McClintock, and M.F. Cameron, 2020: Body condition of phocid seals during a period of rapid environmental change in the Bering Sea and Aleutian Islands, Alaska. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181-182**, 104904–104904. https://doi.org/10.1016/j.dsr2.2020.104904

207. Pagano, A.M., G.M. Durner, T.C. Atwood, and D.C. Douglas, 2021: Effects of sea ice decline and summer land use on polar bear home range size in the Beaufort Sea. *Ecosphere*, **12** (10), 03768. https://doi.org/10.1002/ecs2.3768

208. Taylor, P.C., W. Maslowski, J. Perlwitz, and D.J. Wuebbles, 2017: Ch. 11. Arctic changes and their effects on Alaska and the rest of the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 303-332. https://doi.org/10.7930/j00863gk

209. Ardyna, M. and K.R. Arrigo, 2020: Phytoplankton dynamics in a changing Arctic Ocean. *Nature Climate Change*, **10** (10), 892–903. https://doi.org/10.1038/s41558-020-0905-y

210. Bednaršek, N., K.A. Naish, R.A. Feely, C. Hauri, K. Kimoto, A.J. Hermann, C. Michel, A. Niemi, and D. Pilcher, 2021: Integrated assessment of ocean acidification risks to pteropods in the northern high latitudes: Regional comparison of exposure, sensitivity and adaptive capacity. *Frontiers in Marine Science*, **8**, 671497. https://doi.org/10.3389/fmars.2021.671497

211. Hurst, T.P., B.J. Laurel, E. Hanneman, S.A. Haines, and M.L. Ottmar, 2017: Elevated $CO_2$ does not exacerbate nutritional stress in larvae of a Pacific flatfish. *Fisheries Oceanography*, **26** (3), 336–349. https://doi.org/10.1111/fog.12195

212. Hurst, T.P., B.J. Laurel, J.T. Mathis, and L.R. Tobosa, 2016: Effects of elevated $CO_2$ levels on eggs and larvae of a North Pacific flatfish. *ICES Journal of Marine Science*, **73** (3), 981–990. https://doi.org/10.1093/icesjms/fsv050

213. Hurst, T.P., L.A. Copeman, J.F. Andrade, M.A. Stowell, C.E. Al-Samarrie, J.L. Sanders, and M.L. Kent, 2021: Expanding evaluation of ocean acidification responses in a marine gadid: Elevated $CO_2$ impacts development, but not size of larval walleye pollock. *Marine Biology*, **168** (8), 119. https://doi.org/10.1007/s00227-021-03924-w

214. Hurst, T.P., E.R. Fernandez, and J.T. Mathis, 2013: Effects of ocean acidification on hatch size and larval growth of walleye pollock (*Theragra chalcogramma*). *ICES Journal of Marine Science*, **70** (4), 812–822. https://doi.org/10.1093/icesjms/fst053

215. Hurst, T.P., E.R. Fernandez, J.T. Mathis, J.A. Miller, C.M. Stinson, and E.F. Ahgeak, 2012: Resiliency of juvenile walleye pollock to projected levels of ocean acidification. *Aquatic Biology*, **17** (3), 247–259. https://doi.org/10.3354/ab00483

216. Ou, M., T.J. Hamilton, J. Eom, E.M. Lyall, J. Gallup, A. Jiang, J. Lee, D.A. Close, S.-S. Yun, and C.J. Brauner, 2015: Responses of pink salmon to $CO_2$-induced aquatic acidification. *Nature Climate Change*, **5** (10), 950–955. https://doi.org/10.1038/nclimate2694

217. Long, W.C., S.B. Van Sant, K.M. Swiney, R.J. Foy, W.C. Long, V. Sant, S.B. Swiney, and K.M. Foy, 2017: Survival, growth, and morphology of blue king crabs: Effect of ocean acidification decreases with exposure time. *ICES Journal of Marine Science*, **74** (4), 1033–1041. https://doi.org/10.1093/icesjms/fsw197

218. Long, W.C., K.M. Swiney, and R.J. Foy, 2013: Effects of ocean acidification on the embryos and larvae of red king crab, *Paralithodes camtschaticus*. *Marine Pollution Bulletin*, **69** (1-2), 38–47. https://doi.org/10.1016/j.marpolbul.2013.01.011

219. Long, W.C., K.M. Swiney, C. Harris, H.N. Page, and R.J. Foy, 2013: Effects of ocean acidification on juvenile red king crab (*Paralithodes camtschaticus*) and Tanner crab (*Chionoecetes bairdi*) growth, condition, calcification, and survival. *PLoS ONE*, **8** (4), e60959. https://doi.org/10.1371/journal.pone.0060959

220. Meseck, S.L., J.H. Alix, K.M. Swiney, W.C. Long, G.H. Wikfors, and R.J. Foy, 2016: Ocean acidification affects hemocyte physiology in the tanner crab (*Chionoecetes bairdi*). *PLoS ONE*, **11** (2), 0148477. https://doi.org/10.1371/journal.pone.0148477

221. Swiney, K.M., W.C. Long, and R.J. Foy, 2016: Effects of high $pCO_2$ on Tanner crab reproduction and early life history—Part I: Long-term exposure reduces hatching success and female calcification, and alters embryonic development. *ICES Journal of Marine Science*, **73** (3), 825–835. https://doi.org/10.1093/icesjms/fsv201

222. Tai, T.C., U.R. Sumaila, and W.W.L. Cheung, 2021: Ocean acidification amplifies multi-stressor impacts on global marine invertebrate fisheries. *Frontiers in Marine Science*, **8**, 596644. https://doi.org/10.3389/fmars.2021.596644

223. Hoffman II, H., 2021: Strange Plant Found Below Oskawalik on the Kuskokwim River. LEO Network. https://www.leonetwork.org/en/posts/show/d54b385c-ae44-45a7-82a4-550ced699500

224. Frost, G.V., M.J. Macander, U.S. Bhatt, L.T. Berner, J.W. Bjerke, H.E. Epstein, B.C. Forbes, S.J. Goetz, M.J. Lara, T. Park, G.K. Phoenix, S.P. Serbin, H. Tømmervik, D.A. Walker, and D. Yang, 2021: Arctic Report Card 2021: Tundra Greenness. NOAA Technical Report OAR ARC; 21-08. National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, 8 pp. https://doi.org/10.25923/8n78-wp73

225. Hard, J.S., 1976: Natural control of hemlock sawfly, *Neodiprion tsugae* (Hymenoptera: Diprionidae), populations in Southeast Alaska. *The Canadian Entomologist*, **108** (5), 485–498. https://doi.org/10.4039/ent108485-5

226. Mann, D.H., T.S. Rupp, M.A. Olson, and P.A. Duffy, 2012: Is Alaska's boreal forest now crossing a major ecological threshold? *Arctic, Antarctic, and Alpine Research*, **44** (3), 319–331. https://doi.org/10.1657/1938-4246-44.3.319

227. Thoman, R., 2022: Alaska on fire: Thousands of lightning strikes and a warming climate put Alaska on pace for another historic fire season. *The Conversation*, July 6, 2022. https://theconversation.com/alaska-on-fire-thousands-of-lightning-strikes-and-a-warming-climate-put-alaska-on-pace-for-another-historic-fire-season-186453

228. Scholten, R.C., R. Jandt, E.A. Miller, B.M. Rogers, and S. Veraverbeke, 2021: Overwintering fires in boreal forests. *Nature*, **593** (7859), 399–404. https://doi.org/10.1038/s41586-021-03437-y

229. Chen, Y., M.J. Lara, B.M. Jones, G.V. Frost, and F.S. Hu, 2021: Thermokarst acceleration in Arctic tundra driven by climate change and fire disturbance. *One Earth*, **4** (12), 1718–1729. https://doi.org/10.1016/j.oneear.2021.11.011

230. Lara, M.J., H. Genet, A.D. McGuire, E.S. Euskirchen, Y. Zhang, D.R.N. Brown, M.T. Jorgenson, V. Romanovsky, A. Breen, and W.R. Bolton, 2016: Thermokarst rates intensify due to climate change and forest fragmentation in an Alaskan boreal forest lowland. *Global Change Biology*, **22** (2), 816–829. https://doi.org/10.1111/gcb.13124

231. Lara, M.J., Y. Chen, and B.M. Jones, 2021: Recent warming reverses forty-year decline in catastrophic lake drainage and hastens gradual lake drainage across northern Alaska. *Environmental Research Letters*, **16** (12). https://doi.org/10.1088/1748-9326/ac3602

232. Lindgren, P.R., L.M. Farquharson, V.E. Romanovsky, and G. Grosse, 2021: Landsat-based lake distribution and changes in western Alaska permafrost regions between the 1970s and 2010s. *Environmental Research Letters*, **16** (2). https://doi.org/10.1088/1748-9326/abd270

233. Nitze, I., S. W. Cooley, C. R. Duguay, B. M. Jones, and G. Grosse, 2020: The catastrophic thermokarst lake drainage events of 2018 in northwestern Alaska: Fast-forward into the future. *Cryosphere*, **14** (12), 4279–4297. https://doi.org/10.5194/tc-14-4279-2020

234. Webb, E.E., A.K. Liljedahl, J.A. Cordeiro, M.M. Loranty, C. Witharana, and J.W. Lichstein, 2022: Permafrost thaw drives surface water decline across lake-rich regions of the Arctic. *Nature Climate Change*, **12** (9), 841–846. https://doi.org/10.1038/s41558-022-01455-w

235. Chipman, M.L. and F.S. Hu, 2017: Linkages among climate, fire, and Thermoerosion in Alaskan tundra over the past three millennia. *Journal of Geophysical Research: Biogeosciences*, **122** (12), 3362–3377. https://doi.org/10.1002/2017jg004027

236. Rey, D.M., M.A. Walvoord, B.J. Minsley, B.A. Ebel, C.I. Voss, and K. Singha, 2020: Wildfire-initiated talik development exceeds current thaw projections: Observations and models from Alaska's continuous permafrost zone. *Geophysical Research Letters*, **47** (15). https://doi.org/10.1029/2020gl087565

237. Mekonnen, Z.A., W.J. Riley, R.F. Grant, and V.E. Romanovsky, 2021: Changes in precipitation and air temperature contribute comparably to permafrost degradation in a warmer climate. *Environmental Research Letters*, **16** (2). https://doi.org/10.1088/1748-9326/abc444

238. Jones, B.M., G. Grosse, L.M. Farquharson, P. Roy-Léveillée, A. Veremeeva, M.Z. Kanevskiy, B.V. Gaglioti, A.L. Breen, A.D. Parsekian, M. Ulrich, and K.M. Hinkel, 2022: Lake and drained lake basin systems in lowland permafrost regions. *Nature Reviews Earth & Environment*, **3** (1), 85–98. https://doi.org/10.1038/s43017-021-00238-9

239. McGuire, A.D., H. Genet, Z. Lyu, N. Pastick, S. Stackpoole, R. Birdsey, D. D'Amore, Y. He, T.S. Rupp, R. Striegl, B.K. Wylie, X. Zhou, Q. Zhuang, and Z. Zhu, 2018: Assessing historical and projected carbon balance of Alaska: A synthesis of results and policy/management implications. *Ecological Applications*, **28** (6), 1396–1412. https://doi.org/10.1002/eap.1768

240. Miner, K.R., M.R. Turetsky, E. Malina, A. Bartsch, J. Tamminen, A.D. McGuire, A. Fix, C. Sweeney, C.D. Elder, and C.E. Miller, 2022: Permafrost carbon emissions in a changing Arctic. *Nature Reviews Earth and Environment*, **3** (1), 55–67. https://doi.org/10.1038/s43017-021-00230-3

241. Schuur, E.A.G., R. Bracho, G. Celis, E.F. Belshe, C. Ebert, J. Ledman, M. Mauritz, E.F. Pegoraro, C. Plaza, H. Rodenhizer, V. Romanovsky, C. Schädel, D. Schirokauer, M. Taylor, J.G. Vogel, and E.E. Webb, 2021: Tundra underlain by thawing permafrost persistently emits carbon to the atmosphere over 15 years of measurements. *Journal of Geophysical Research: Biogeosciences*, **126** (6), e2020JG006044. https://doi.org/10.1029/2020jg006044

242. Arimitsu, M.L., J.F. Piatt, S. Hatch, R.M. Suryan, S. Batten, M.A. Bishop, R.W. Campbell, H. Coletti, D. Cushing, K. Gorman, R.R. Hopcroft, K.J. Kuletz, C. Marsteller, C. McKinstry, D. McGowan, J. Moran, S. Pegau, A. Schaefer, S. Schoen, J. Straley, and V.R. von Biela, 2021: Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. *Global Change Biology*, **27** (9), 1859–1878. https://doi.org/10.1111/gcb.15556

243. Jones, L.A., E.R. Schoen, R. Shaftel, C.J. Cunningham, S. Mauger, D.J. Rinella, and A. St. Saviour, 2020: Watershed-scale climate influences productivity of Chinook salmon populations across southcentral Alaska. *Global Change Biology*, **26** (9), 4919–4936. https://doi.org/10.1111/gcb.15155

244. Armstrong, J.B., E.J. Ward, D.E. Schindler, and P.J. Lisi, 2016: Adaptive capacity at the northern front: Sockeye salmon behaviourally thermoregulate during novel exposure to warm temperatures. *Conservation Physiology*, **4** (1). https://doi.org/10.1093/conphys/cow039

245. Pitman, K.J., J.W. Moore, M. Huss, M.R. Sloat, D.C. Whited, T.J. Beechie, R. Brenner, E.W. Hood, A.M. Milner, G.R. Pess, G.H. Reeves, and D.E. Schindler, 2021: Glacier retreat creating new Pacific salmon habitat in western North America. *Nature Communications*, **12** (1), 6816. https://doi.org/10.1038/s41467-021-26897-2

246. Carey, M.P., V.R. von Biela, R.J. Brown, and C.E. Zimmerman, 2021: Migration strategies supporting salmonids in Arctic Rivers: A case study of Arctic Cisco and Dolly Varden. *Animal Migration*, **8** (1), 132–143. https://doi.org/10.1515/ami-2020-0115

247. DOD, 2021: Department of Defense Climate Risk Analysis. Report Submitted to National Security Council. U.S. Department of Defense, Office of the Undersecretary for Policy, 18 pp. https://media.defense.gov/2021/oct/21/2002877353/-1/-1/0/dod-climate-risk-analysis-final.pdf

248. DOD, 2019: Report to Congress on Military Structure in Permafrost Areas. U.S. Department of Defense, Office of The Under Secretary of Defense. https://www.acq.osd.mil/eie/downloads/fim/2019%20report%20to%20congress%20on%20military%20structures%20in%20permafrost%20areas.pdf

249. Hjort, J., O. Karjalainen, J. Aalto, S. Westermann, V.E. Romanovsky, F.E. Nelson, B. Etzelmüller, and M. Luoto, 2018: Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications*, **9** (1), 5147. https://doi.org/10.1038/s41467-018-07557-4

250. BLM AFS, 2022: Prescribed Burn Operations Planned on Military Training Lands in the Fairbanks North Star Borough to Reduce Wildfire Threat. U.S. Department of Interior, Bureau of Land Managment, Alaska Fire Service, Fairbanks, AK. https://akfireinfo.files.wordpress.com/2022/05/afs_fwa-yta_2022newrelease.pdf

251. CMTS, 2019: A Ten-Year Projection of Maritime Activity in the U.S. Arctic Region, 2020–2030. U.S. Committee on the Marine Transportation System, Washington, DC, 118 pp. https://www.cmts.gov/assets/uploads/documents/cmts_2019_arctic_vessel_projection_report.pdf

252. Boulègue, M., 2019: *Russia's Military Posture in the Arctic*. Chatham House. https://www.chathamhouse.org/2019/06/russias-military-posture-arctic

253. Pezard, S., S.J. Flanagan, S.W. Harold, I.A. Chindea, B.J. Sacks, A. Tingstad, T. Finazzo, and S. Kim, 2022: China's Strategy and Activities in the Arctic: Implications for North American and Transatlantic Security. RAND Corporation, Santa Monica, CA. https://doi.org/10.7249/rra1282-1-v2

254. NOAA Marine Debris Program, 2021: Bering Strait Marine Debris Event Report. National Oceanic and Atmospheric Administration, National Ocean Service, Office of Response and Restoration, Marine Debris Program, Silver Spring, MD. https://marinedebris.noaa.gov/emergency-response/bering-strait-marine-debris-event-report

255. DHS, 2019: Strategic Approach for Arctic Homeland Security. U.S. Department of Homeland Security, Office of Strategy, Policy, and Plans, 25 pp. https://www.dhs.gov/sites/default/files/publications/21_0113_plcy_dhs-arctic-strategy_0.pdf

256. USAF, 2020: The Department of the Air Force Arctic Strategy. U.S. Air Force. https://www.af.mil/portals/1/documents/2020saf/july/arcticstrategy.pdf

257. Hudson, A., 2022: Eielson days away from achieving full complement of F-35s. *Air & Space Forces Magazine*. https://www.airforcemag.com/eielson-days-away-from-achieving-full-complement-of-f-35s/

258. Bennett, M.M., S.R. Stephenson, K. Yang, M.T. Bravo, and B. De Jonghe, 2020: The opening of the Transpolar Sea Route: Logistical, geopolitical, environmental, and socioeconomic impacts. *Marine Policy*, **121**, 104178. https://doi.org/10.1016/j.marpol.2020.104178

259. Henry Huntington (Chapter Lead), October 19, 2022: Email communication with Jacqueline Christensen, Native Village of Port Heiden (Alaska).

260. Henry Huntington (Chapter Lead), August 29, 2022: Email communication with Theo Garcia, Knik Tribal Council (Alaska).

261. Canosa, I.V., J.D. Ford, G. McDowell, J. Jones, and T. Pearce, 2020: Progress in climate change adaptation in the Arctic. *Environmental Research Letters*, **15** (9), 093009. https://doi.org/10.1088/1748-9326/ab9be1

262. Adapt Alaska, 2022: Adapt Alaska: Resources. University of Alaska, Fairbanks. https://adaptalaska.org/resources/

263. Hahn, M.B., C. Kemp, C. Ward-Waller, S. Donovan, J.I. Schmidt, and S. Bauer, 2020: Collaborative climate mitigation and adaptation planning with university, community, and municipal partners: A case study in Anchorage, Alaska. *Local Environment*, **25** (9), 648–665. https://doi.org/10.1080/13549839.2020.1811655

264. Steffen, A., S.A. Greenlaw, M. Biermann, and A.L. Lovecraft, 2021: Alaska's Climate Change Policy Development. University of Alaska, Center for Arctic Policy Studies, Fairbanks, AK, 59 pp. https://www.uaf.edu/caps/our-work/CAPS-alaskas-climate-policy-development-March2021-corrected.pdf

265. Birchall, J.S. and N. Bonnett, 2020: Thinning sea ice and thawing permafrost: Climate change adaptation planning in Nome, Alaska. *Environmental Hazards*, **19** (2), 152–170. https://doi.org/10.1080/17477891.2019.1637331

266. Birchall, S.J. and N. Bonnett, 2019: Local-scale climate change stressors and policy response: The case of Homer, Alaska. *Journal of Environmental Planning and Management*, **62** (13), 2238–2254. https://doi.org/10.1080/09640568.2018.1537975

267. Bronen, R., D. Pollock, J. Overbeck, D. Stevens, S. Natali, and C. Maio, 2020: Usteq: Integrating indigenous knowledge and social and physical sciences to coproduce knowledge and support community-based adaptation. *Polar Geography*, **43** (2-3), 188–205. https://doi.org/10.1080/1088937x.2019.1679271

268. DCRA, n.d.: Community Resilience and Climate Adaptation Programs. Alaska Department of Commerce, Community, and Economic Development, Division of Community and Regional Affairs. https://www.commerce.alaska.gov/web/dcra/CommunityResilienceandClimateAdaptationPrograms.aspx

269. AMAP, 2017: Adaptation Actions for a Changing Arctic: Perspectives From the Beringchukchi-Beaufort Region. Arctic Monitoring and Assessment Programme, Oslo, Norway. https://www.amap.no/documents/download/2993

270. ICC Alaska, 2020: Food Sovereignty and Self-Governance: Inuit Role in Managing Arctic Marine Resources. Inuit Circumpolar Council Alaska, Anchorage, AK. https://www.inuitcircumpolar.com/project/food-sovereignty-and-self-governance-inuit-role-in-managing-arctic-marine-resources/

271. Loring, P.A., S.C. Gerlach, and H.J. Penn, 2016: "Community work" in a climate of adaptation: Responding to change in rural Alaska. *Human Ecology*, **44** (1), 119–128. https://doi.org/10.1007/s10745-015-9800-y

272. BIA, n.d.: Tribal Climate Resilience Program Awards. Bureau of Indian Affairs. https://biamaps.doi.gov/portal/apps/webappviewer/index.html?id=19ad66da24704639b09ae64a81154eb4

273. ANTHC, 2023: Assessment Reports Archive. Alaska Native Tribal Health Consortium. https://www.anthc.org/what-we-do/community-environment-and-health/center-for-climate-and-health/climate-health-3/

274. Chase, M., K. Heeringa, J. Littell, R. Toohey, and M. Tankersley, 2020: Looking Forward, Looking Back: Building Resilience Today: Training Two Report. Aleutian Pribilof Islands Association, Fairbanks, AK, 26 pp. https://pubs.er.usgs.gov/publication/70243265

275. Beck, C.A., H.L. Stewart, and I. Dutton, 2019: Adapt Y-K Delta: Climate Adaptation Strategies for the Yukon-Kuskokwim (Y-K) Delta Region. Adapt Y-K Delta Steering Committee, Anchorage, AK. https://adaptalaska.org/wp-content/uploads/2020/01/ADAPT-YK_Strategies_FINAL_sm.pdf

276. CCTHITA, 2019: Climate Change Adaptation Plan. Central Council of the Tlingit and Haida Indian Tribes of Alaska. http://www.ccthita.org/services/community/environmental/documents/t%26hclimatechangeadaptationplan.pdf

277. Blair, B. and G.P. Kofinas, 2020: Cross-scale risk perception: Differences between tribal leaders and resource managers in Arctic Alaska. *Ecology and Society*, **25** (4). https://doi.org/10.5751/es-11776-250409

278. Ellam Yua, J. Raymond-Yakoubian, R. Aluaq Daniel, and C. Behe, 2022: A framework for co-production of knowledge in the context of Arctic research. *Ecology and Society*, **27** (1), 34. https://doi.org/10.5751/es-12960-270134

279. Carlo, N., 2020: Arctic Observing: Indigenous Peoples' History, Perspectives, and Approaches for Partnership. University of Alaska, Center for Arctic Policy Studies, Fairbanks, AK. https://www.uaf.edu/caps/our-work/Carlo_Arctic-Observing_Indigenous-Peoples-History_CAPS_5MAR2020.pdf

280. ANKN, 2006: Alaska Native Values for the Curriculum. University of Alaska Fairbanks, Alaska Native Knowledge Network. http://www.ankn.uaf.edu/ancr/values/

281. Berman, M., J. Baztan, G. Kofinas, J.P. Vanderlinden, O. Chouinard, J.M. Huctin, A. Kane, C. Mazé, I. Nikulkina, and K. Thomson, 2020: Adaptation to climate change in coastal communities: Findings from seven sites on four continents. *Climatic Change*, **159** (1), 1–16. https://doi.org/10.1007/s10584-019-02571-x

282. CCTHITA, n.d.: Southeast Traditional Tribal Values. Central Council of the Tlingit and Haida Indian Tribes of Alaska. http://www.ccthita.org/about/values/index.html

283. Curry, T., C. Meek, and M. Berman, 2021: Informal institutions and adaptation: Patterns and pathways of influence in a remote Arctic community. *Local Environment*, **26** (9), 1070–1091. https://doi.org/10.1080/13549839.2021.1962828

284. Fauchald, P., V.H. Hausner, J.I. Schmidt, and D.A. Clark, 2017: Transitions of social-ecological subsistence systems in the Arctic. *International Journal of the Commons*, **11** (1), 275–329. https://doi.org/10.18352/ijc.698/metrics/

285. Figus, E., B.K.Y. Jackson, and S.F. Trainor, 2022: The Kake Climate Partnership: Implementing a knowledge co-production framework to provide climate services in Southeast Alaska. *Frontiers in Climate*, **4**, 885494. https://doi.org/10.3389/fclim.2022.885494

286. GAO, 2022: Alaska Native Issues: Federal Agencies Could Enhance Support for Native Village Efforts to Address Environmental Threats. GAO-22-104241. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-22-104241.pdf

287. Ristroph, E.B., 2022: How Alaska Native corporations can better support Alaska Native villages. *American Indian Law Journal*, **10** (1), 5. https://digitalcommons.law.seattleu.edu/ailj/vol10/iss1/5

288. Adaptation Advisory Group, 2010: Alaska's Climate Change Strategy: Addressing Impacts in Alaska. Georgetown Climate Center. https://www.adaptationclearinghouse.org/resources/alaska-s-climate-change-strategy-addressing-impacts-in-alaska.html

289. Nakashima, D.J., K. Galloway McLean, H.D. Thulstrup, A. Ramos Castillo, and J.T. Rubis, 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation*. UNESCO, Paris and Darwin, UNU, 120 pp. https://unesdoc.unesco.org/ark:/48223/pf0000216613

290. Naylor, A., J. Ford, T. Pearce, and J. Van Alstine, 2020: Conceptualizing climate vulnerability in complex adaptive systems. *One Earth*, **2** (5), 444–454. https://doi.org/10.1016/j.oneear.2020.04.011

291. Alaska Native Claims Settlement Act. Pub. L. No. 92–203, 85 Stat. 688, December 18, 1971. https://uscode.house.gov/view.xhtml?path=/prelim@title43/chapter33&edition=prelim

292. Ristroph, E.B., 2021: Navigating climate change adaptation assistance for communities: A case study of Newtok Village, Alaska. *Journal of Environmental Studies and Sciences*, **11** (3), 329–340. https://doi.org/10.1007/s13412-021-00711-3

293. Ristroph, E., 2019: Fulfilling climate justice and government obligations to Alaska Native villages: What is the government role? *William & Mary Environmental Law and Policy Review*, **43** (2). https://scholarship.law.wm.edu/wmelpr/vol43/iss2/4

294. The Alaska Center, 2017: Solarize Your Community [Website], accessed April 4, 2023. https://akcenter.org/climate-clean-energy/solarize/

295. Solarize the Kenai, 2021: Solarize the Kenai [Website], accessed April 4, 2023. https://www.solarizethekenai.org/

296. Alaska Heat Smart, n.d.: Thermalize Juneau [Webpage], accessed April 3, 2023. https://akheatsmart.org/programs/thermalize-juneau/

297. AEL&P, 2016: Alternative Energy. Alaska Electric Light and Power, Juneau, AK, accessed April 4, 2023. https://www.aelp.com/energy-conservation/alternative-energy

298. Chugach Electric Association, 2023: Energy Solutions: Net Metering and Buyback Generation [Webpage], accessed April 4, 2023. https://www.chugachelectric.com/energy-solutions/net-metering-and-buyback-generation

299. GVEA, 2018: GVEA's Solar Farm. Golden Valley Electric Association, accessed April 3, 2023. https://www.gvea.com/services/energy/sources-of-power/gveas-solar-farm/

300. Juneau Electric Vehicle Association, n.d.: Juneau EV [Website], accessed April 3, 2023. https://juneauev.org/

301. BuyAlaska, 2023: Community Supported Agriculture [Website], accessed April 5, 2023. https://buyalaska.com/csa/

302. Naiden, A., 2021: Donated salmon gets shipped to communities on the Yukon. *Fairbanks Daily News-Miner*, August 6, 2021. https://www.newsminer.com/news/alaska_news/donated-salmon-gets-shipped-to-communities-on-the-yukon/article_52d45244-f622-11eb-9bd2-7f6bc3fca171.html

303. Bonnett, N. and S.J. Birchall, 2020: Coastal communities in the Circumpolar North and the need for sustainable climate adaptation approaches. *Marine Policy*, **121**, 104175. https://doi.org/10.1016/j.marpol.2020.104175

304. Ford, J.D., T. Pearce, I.V. Canosa, and S. Harper, 2021: The rapidly changing Arctic and its societal implications. *Wiley Interdisciplinary Reviews: Climate Change*, **12** (6), e735–e735. https://doi.org/10.1002/wcc.735

305. Huntington, H.P., M. Carey, C. Apok, B.C. Forbes, S. Fox, L.K. Holm, A. Ivanova, J. Jaypoody, G. Noongwook, and F. Stammler, 2019: Climate change in context: Putting people first in the Arctic. *Regional Environmental Change*, **19** (4), 1217–1223. https://doi.org/10.1007/s10113-019-01478-8

306. Adger, W.N., J.M. Pulhin, J. Barnett, G.D. Dabelko, G.K. Hovelsrud, M. Levy, S. Ú. Oswald, and C.H. Vogel, 2014: Ch. 12. Human security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755-791. https://www.ipcc.ch/report/ar5/wg2/human-security/

307. David-Chavez, D.M. and M.C. Gavin, 2018: A global assessment of Indigenous community engagement in climate research. *Environmental Research Letters*, **13** (12), 123005. https://doi.org/10.1088/1748-9326/aaf300

308. Roy, J., P. Tschakert, H. Waisman, S. Abdul Halim, P. Antwi-Agyei, P. Dasgupta, B. Hayward, M. Kanninen, D. Liverman, C. Okereke, P.F. Pinho, K. Riahi, and A.G. Suarez Rodriguez, 2018: Ch. 5. Sustainable development, poverty eradication and reducing inequalities. In: *Global Warming of 1.5°C. an IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts To Eradicate Poverty*. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 445–538. https://doi.org/10.1017/9781009157940.007

309. Morales, K., C. Avery, M. Chase, K. Cozzetto, P. Ezcurra, P. Hardison, A. Herrmann, H. Mullen, and K. Whyte, 2021: Ch. 12. Emerging topics. In: *Status of Tribes and Climate Change Report*. Marks-Marino, D., Ed. Institute for Tribal Environmental Professionals, 277–295. http://nau.edu/stacc2021

310. The White House, 2022: White House Releases First-of-a-Kind Indigenous Knowledge Guidance for Federal Agencies. The White House. https://www.whitehouse.gov/ceq/news-updates/2022/12/01/white-house-releases-first-of-a-kind-indigenous-knowledge-guidance-for-federal-agencies/

311. Sparrow, E., C. Keill, C. Breest, T. Clucas, and T. Moran, 2017: Innovative experiences in STEM education. In: *INTED2017 Proceedings: 11th International Technology, Education and Development Conference*, Chova, L.G., A.L. Martínez, and I.C. Torres, Eds. Valencia, Spain, 6–8 March 2017, 7619–7628. https://doi.org/10.21125/inted.2017

312. Sparrow, E.B. and S. Yule, 2010: Seasons and biomes and the GLOBE Program: Monitoring seasons through global learning communities. In: *Polar Science and Global Climate: An International Resource for Education & Outreach*, Kaiser, B., Ed. London, UK. Pearson, 152–153. https://polareducator.org/resources/prb-2/

313. Yoshikawa, K., E. Sparrow, and J. Stanilovskaya, 2014: Engaging Alaska communities and students in cryospheric research. In: *Geoscience Research and Outreach: Schools and Public Engagement*. Tong, V.C.H., Ed. Springer, Dordrecht, Netherlands, 19–45. https://doi.org/10.1007/978-94-007-6943-4_3

314. Gazal, R., M.A. White, R. Gillies, E. Rodemaker, E. Sparrow, and L. Gordon, 2008: GLOBE students, teachers, and scientists demonstrate variable differences between urban and rural leaf phenology. *Global Change Biology*, **14** (7), 1568–1580. https://doi.org/10.1111/j.1365-2486.2008.01602.x

315. Robin, J., R. Dubayah, E. Sparrow, and E. Levine, 2008: Monitoring start of season in Alaska with GLOBE, AVHRR, and MODIS data. *Journal of Geophysical Research: Biogeosciences*, **113** (G1). https://doi.org/10.1029/2007jg000407

316. Spellman, K.V., E.B. Sparrow, M.J. Chase, A. Larson, and K. Kealy, 2018: Connected climate change learning through citizen science: An assessment of priorities and needs of formal and informal educators and community members in Alaska. *Connected Science Learning*, **1** (6). https://www.nsta.org/connected-science-learning/connected-science-learning-april-june-2018-0/connected-climate-change

317. Hauser, D.D.W., R.T. Glenn, E.D. Lindley, K.K. Pikok, K. Heeringa, J. Jones, B. Adams, J.M. Leavitt, G.N. Omnik, R. Schaeffer, C. SimsKayotuk, E.B. Sparrow, A.M. Ravelo, O. Lee, and H. Eicken, 2023: Nunaaqqit Savaqatigivlugich—Working with communities: Evolving collaborations around an Alaska Arctic observatory and knowledge hub. *Arctic Science*, **9** (3), 635–656. https://doi.org/10.1139/as-2022-0044

318. Chase, M., F. Olin IV, and H. Stewart., 2021: Adaptation Planning Pathways Coordinated Pathways. Aleutian Pribilof Islands Association and Agnew, Anchorage, AK. [Print].

319. Willow Hetrick (Technical Contributor), December 16, 2020: Oral communication with Dune Lankard (Eyak Athabascan), Copper River Delta, Alaska.

320. Fedewa, E.J., T.M. Jackson, J.I. Richar, J.L. Gardner, and M.A. Litzow, 2020: Recent shifts in northern Bering Sea snow crab (*Chionoecetes opilio*) size structure and the potential role of climate-mediated range contraction. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181–182**, 104878. https://doi.org/10.1016/j.dsr2.2020.104878

321. Ford, J.D., G. McDowell, and T. Pearce, 2015: The adaptation challenge in the Arctic. *Nature Climate Change*, **5** (12), 1046–1053. https://doi.org/10.1038/nclimate2723

322. *Solving the Climate Crisis: Key Accomplishments, Additional Opportunities, and the Need for Continued Action, House Select Committee on the Climate Crisis*, 2022: 117 Congress. https://www.congress.gov/event/117th-congress/house-event/115211?s=1&r=70

323. The White House, 2021: Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability. The White House. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/

324. LaFrance, J. and R. Nichols, 2008: Reframing evaluation: Defining an Indigenous evaluation framework. *Canadian Journal of Program Evaluation*, **23** (2), 13–31. https://psycnet.apa.org/record/2010-10284-001

Fifth National Climate Assessment: Chapter 30

# Hawai‘i and US-Affiliated Pacific Islands

# Chapter 30. Hawai‘i and US-Affiliated Pacific Islands

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# Introduction

*Moananuiākea*, Hawaiian for the Pacific Ocean, connects a diverse group of island peoples who share reciprocal and spiritual relationships with the lands, waters, natural resources, and cultures of the region. Indigenous Knowledge systems derived from thousands of years of stewardship and underlying observations have sustained Pacific Islanders, as evidenced in the cultural practices of seafaring,[1] canoe building, agroforestry (a farming system that includes trees),[2,3,4,5] harvesting fish and other marine life,[6,7,8] traditional medicine,[9] and managing water.[10]

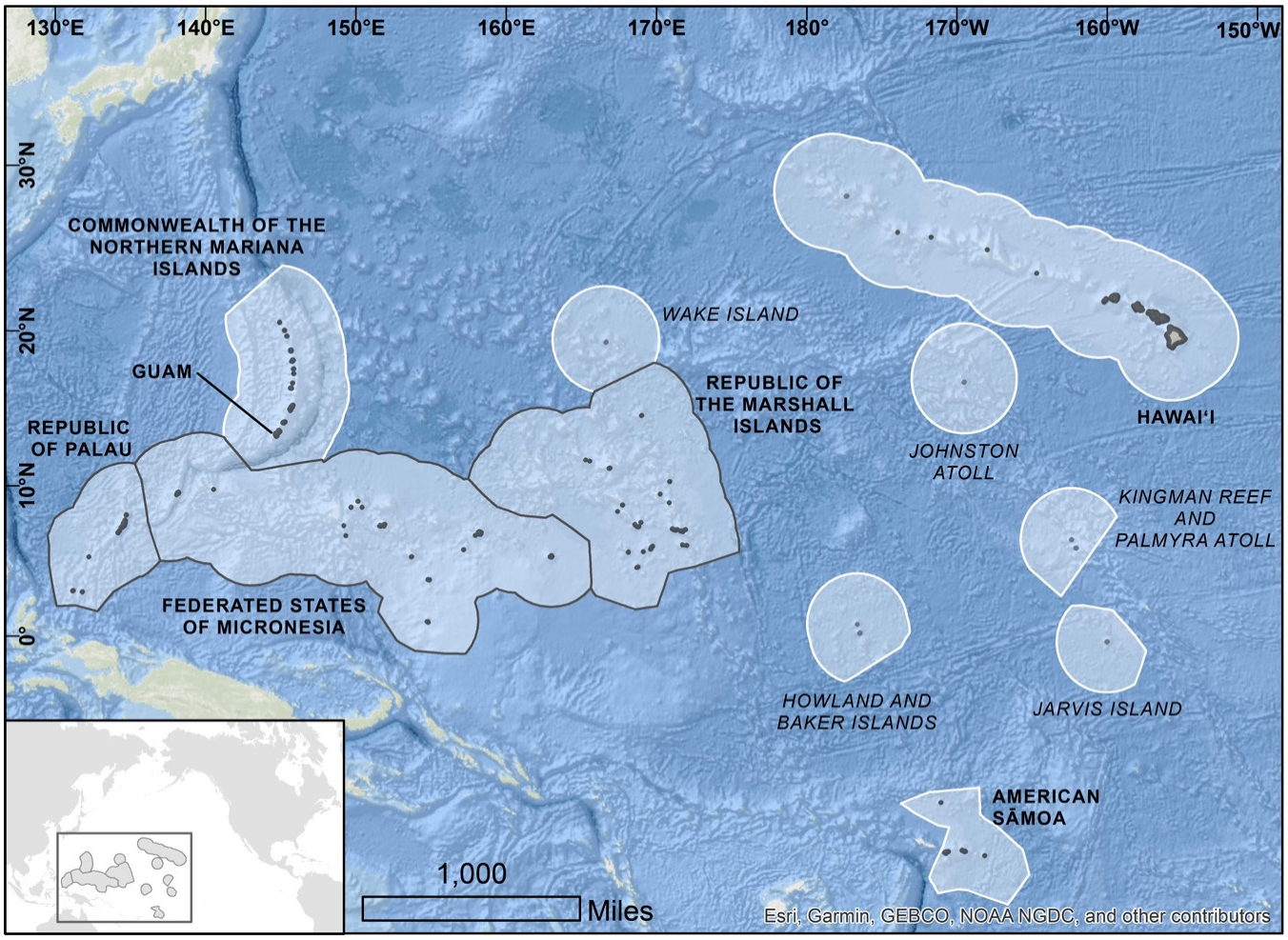
The Pacific Islands region is defined here as Hawai'i and the US-Affiliated Pacific Islands (USAPI). The USAPI comprises the Commonwealth of the Northern Mariana Islands (CNMI); the unincorporated territories of American Sāmoa, Guam, and the Pacific Remote Islands (PRI); and the Freely Associated States (FAS): the Federated States of Micronesia (FSM), the Republic of the Marshall Islands (RMI), and the Republic of Palau. The region spans a vast geography and encompasses over 2,000 islands, ranging from small low-lying atolls to large volcanic islands, with the highest peak rising to 13,803 feet (Figures 30.1, 30.2). Marine and terrestrial biodiversity and species endemism are exceptionally high. These islands (excluding FAS) total only 14,060 square miles in land area but define nearly half (47.2%) of the entire US exclusive economic zone (EEZ). The islands also support more than two dozen defense installations key to US security, including the headquarters for the US Indo-Pacific Command. As a consequence of colonization, the lands, waters, and peoples of the Pacific Islands were significantly involved in World War II,[11] resulting in widespread environmental devastation, displacement of Indigenous Peoples, and nuclear weapons testing.[12,13,14]

The 1.9 million people who call the region home are predominantly (more than 77%) Pacific Islanders, many of whom are Indigenous Peoples (CHamoru, Chuukese, Kosraean, Marshallese, Native Hawaiian, Palauan, Pohnpeian, Samoan, Yapese, and others)—who speak more than 20 Indigenous languages[15]—and members of diverse communities of Asian heritage. Population is declining on all islands (except Hawai'i) and is increasingly urban.[16,17,18,19,20,21,22] Important economic sectors include tourism, agriculture, and fishing, with government assistance, foreign direct investment, and remittances as major sources of capital. Average per capita income ranges from a high of 124% above the US average in Hawai'i to 4%–20% in the FAS.[22,23,24] Governance arrangements across the islands vary, but all share histories of colonization that contribute to structural inequities and vulnerabilities that exacerbate the social and economic impacts of climate change (Box 30.1).[14,25]

## Box 30.1. Historical Under-Resourcing Results in Continuing Data Inequities for the Pacific Islands Region and US Caribbean

The Pacific Islands region and the US Caribbean continue to face similar climate change–related challenges (Ch. 23; see Keener et al. 2018[26]), including geographic isolation and reliance on imports, critical dependence on local natural resources (fresh water, fisheries), and vulnerabilities to drought, sea level rise (SLR), and natural disasters. Missing data in both regions is representative of ongoing exclusion in data collection efforts and perpetuates historical social injustices that are reinforced by colonial and postcolonial governance systems (KM 31.2). In the Pacific Islands, this has resulted in sparse and discontinuous climate data records, the absence of coastal flood hazard modeling and detailed SLR exposure mapping for most islands, a lack of downscaled future climate projections in most locations (App. 3), insufficient information about groundwater and surface water resources, and limited data on ecosystem response.[15,27,28,29,30] Similar gaps are apparent in socioeconomic and health data: for example, on migration and health outcomes, including morbidity and mortality related to extreme weather events; food supply chain vulnerabilities; and resource-dependent livelihoods.[31,32,33,34] Indigenous Knowledge systems and stewardship are foundational in responding to climate change, but generations of knowledge have been undervalued, suppressed, and ignored by Western science and were only recently recognized as valid knowledge sources at the federal level.[35,36,37] This lack of climate-relevant data is evident throughout NCA5. Filling these data gaps could better enable data-driven decision-making and improve climate services in the region.

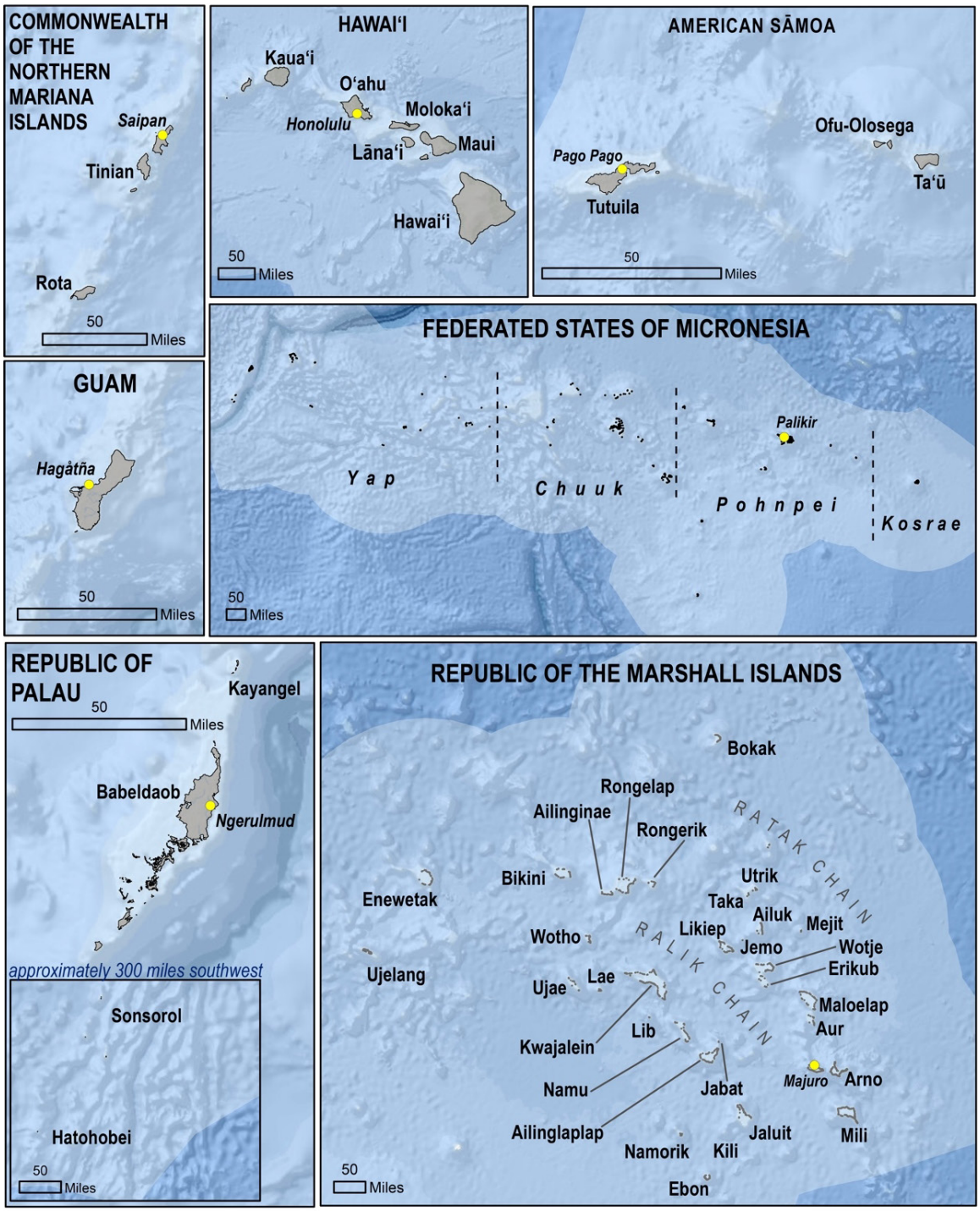
## Hawai‘i and the US-Affiliated Pacific Islands




**Hawai‘i and the US-Affiliated Pacific Islands span a vast geography.**

**Figure 30.1.** The map shows the geographic breadth of the state of Hawai’i and the US-Affiliated Pacific Islands (USAPI). The USAPI comprises the US territories of American Sāmoa, Guam, and the Pacific Remote Islands (Baker Island, Howland Island, Jarvis Island, Johnston Atoll, Kingman Reef, Palmyra Atoll, and Wake Island); the Commonwealth of the Northern Mariana Islands; and the Freely Associated States: the Federated States of Micronesia, the Republic of the Marshall Islands, and the Republic of Palau. The exclusive economic zones around each jurisdiction are shown. Figure credit: University of Guam, Clark University, NOAA NCEI, and CISESS NC. Sources: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors. Map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved.

## Detailed View of Hawai‘i and the US-Affiliated Pacific Islands




Service Layer Credits: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

**The Pacific Islands region contains a diversity of high and low islands.**

**Figure 30.2.** These detailed maps show the inhabited Pacific Islands region with islands and capital cities labeled. Shown are American Sāmoa; the Commonwealth of the Northern Mariana Islands; the Federated States of Micronesia (with its four states labeled: Yap, Chuuk, Pohnpei, and Kosrae); Guam; Hawai‘i; the Republic of the Marshall Islands; and the Republic of Palau. Figure credit: Clark University, Arizona State University, University of Guam, NOAA NCEI, and CISESS NC. Sources: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors. Map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved.

## Climate Variability and Change

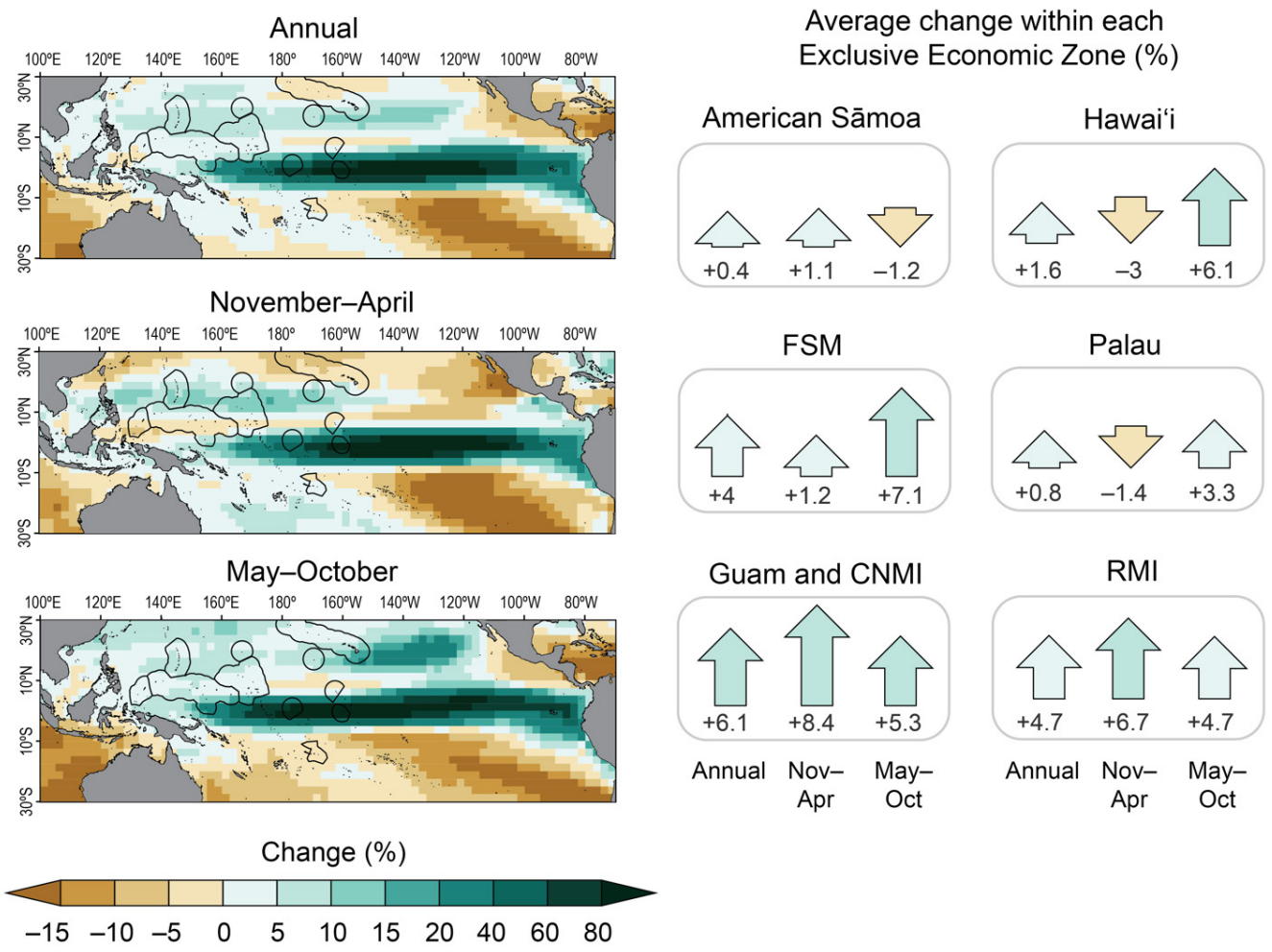
The El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (KMs 2.1, 3.3) are dominant sources of climate variability in the Pacific Islands region, affecting rainfall, air and ocean temperature, sea surface height, and trade winds (Box 27.1 in Keener et al. 2018[38]).[30,39,40,41] ENSO and other sources of climate variability interact with climate change to reduce or amplify trends and their impacts on decadal and shorter timescales. Natural variability in sea level and tides, for example, affects tidal flooding experienced at various Pacific Island locations.[42,43,44]

Between 1951 and 2020, annual average air temperatures across the Pacific Islands region increased 2°F (1°C).[45,46] End-of-century projections indicate up to 4.5°F (2.5°C) higher temperatures at high elevations (above 9,800 feet) for an intermediate scenario (RCP4.5) and up to 9°F (5°C) under a very high scenario (RCP8.5).[47] Historical precipitation trends are variable across the region, with some islands seeing long-term drying and increases in drought frequency, severity, and duration (KM 4.1).[48,49,50] The magnitude and direction of projected precipitation changes are currently highly uncertain (Figure 30.3); some areas are projected to experience drying (e.g., leeward [western] areas of Hawai'i;[51] KM 2.1), while increases in precipitation are expected for others (e.g., American Sāmoa).[52]

Although the findings are uncertain and geographically diverse, current analyses indicate that the frequency of tropical cyclones is expected to decrease,[53] but associated wind speeds, rainfall rates, and storm surge heights are projected to increase across the entire region (KM 2.2).[53,54,55,56,57]

The rate of increase in regional sea surface temperatures (SSTs) has exceeded global rates, while ocean acidification (declining ocean pH)[58] in the region has reached levels not seen over the past 30 years.[59] These region-wide changes are projected to continue over the remainder of this century,[60] with dire consequences for coral reef ecosystems (KM 10.1).[61,62] Relative sea level rise (SLR) rates vary across the Pacific region,[63] with the highest SLR rates observed in the western Pacific.[64] With warming above 3.6°F (2°C), SLR projections of 3.5 to 7.5 feet by 2100 are increasingly possible (Figure 30.4; KM 9.1).[65]

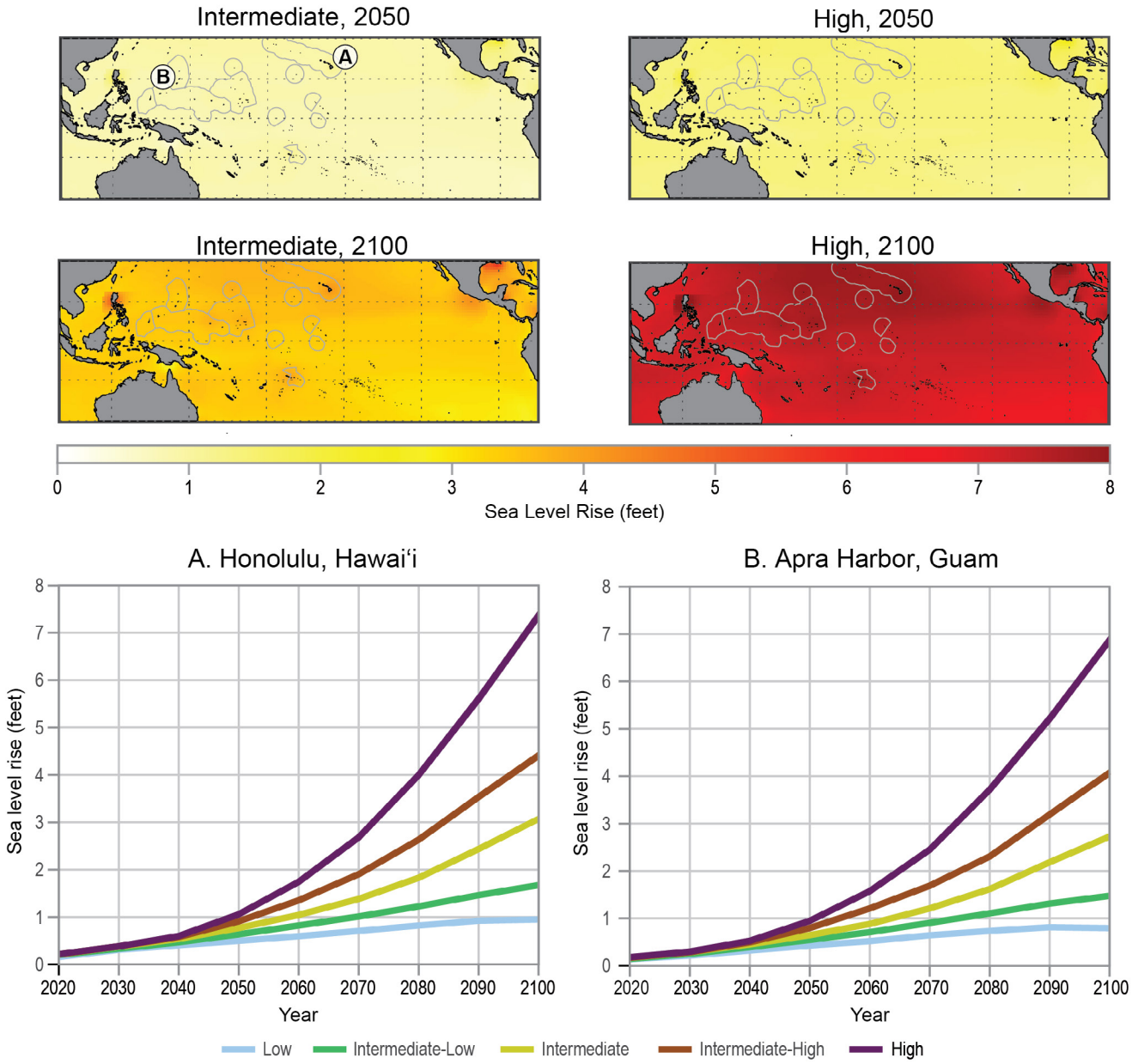
## Projected Changes in Rainfall at 3°C (5.4°F) of Global Warming (Relative to 1985–2014)




**Rainfall is projected to increase across most of the region with 3°C (5.4°F) of global warming.**

**Figure 30.3.** The figure shows projected percent change in annual and seasonal rainfall by 2100 across the Pacific Islands region under a global warming level of 3°C (5.4°F) relative to 1985–2014. Large increases in future rainfall are seen for the Commonwealth of the Northern Mariana Islands (CNMI), the Federated States of Micronesia (FSM), Guam, and the Republic of the Marshall Islands (RMI), while almost no change is projected for American Sāmoa. Hawai‘i and Palau are projected to see decreases in November–April rainfall and increases in May–October rainfall. Adapted from Dhage and Widlansky 2022[66] [CC BY 4.0].

## Regional Sea Level Rise Projections



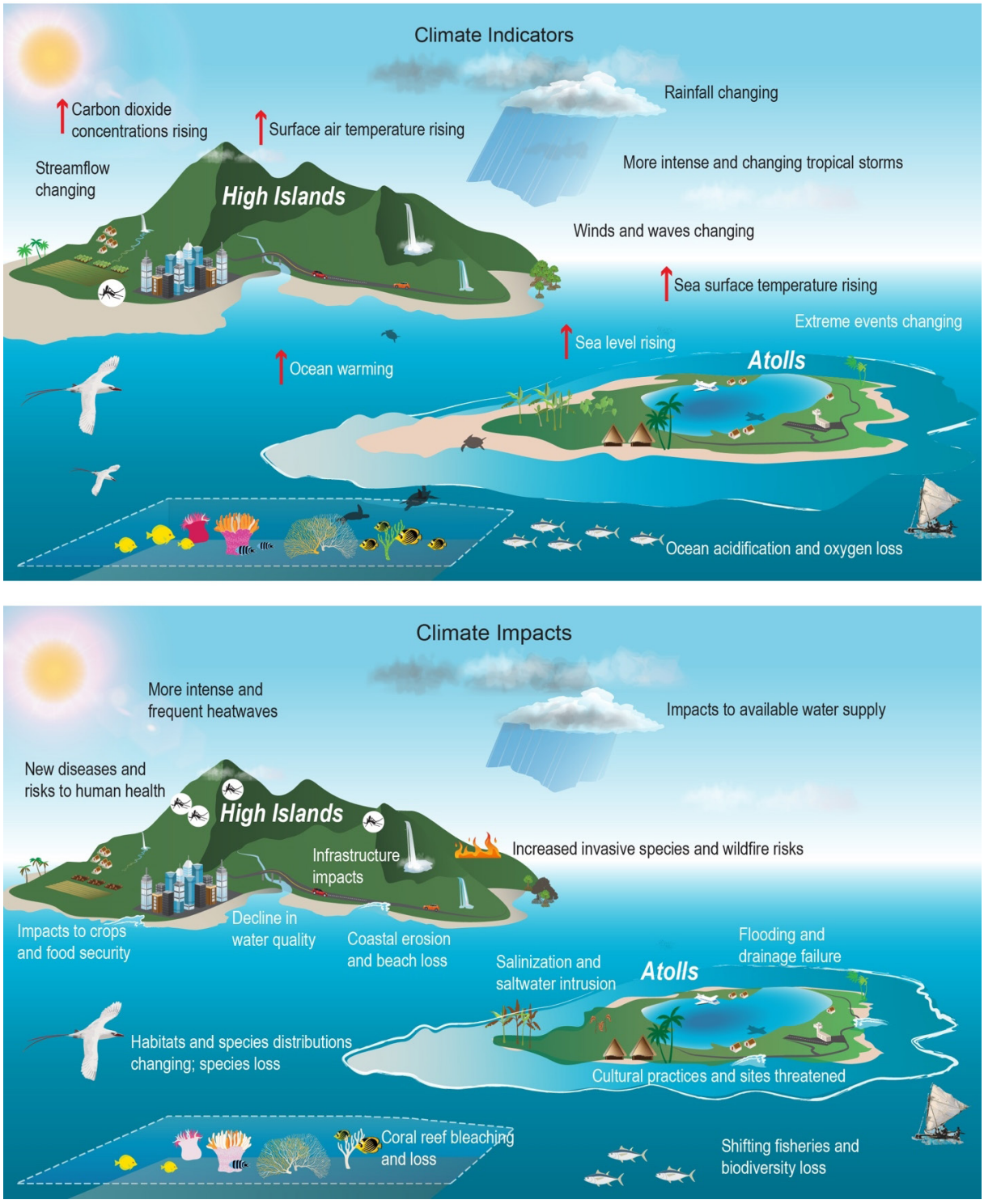

**Future sea levels strongly depend on the scenario, and rates will vary across the region.**

**Figure 30.4.** Sea level rise (SLR) projections for different scenarios are as follows: Low (1 foot of global SLR by 2100), Intermediate-Low (1.5 feet), Intermediate (3 feet), Intermediate-High (5 feet), and High (6.5 feet). (**top four panels**) Maps display regional variations in projected SLR by 2050 (top row) and 2100 (center row) in the Pacific under Intermediate (left) and High (right) scenarios. In general, sea levels are relatively higher in the northern and western Pacific than in the southern and eastern Pacific. Although patterns vary spatially due to various processes such as thermal expansion and subsidence, the greatest sources of variability are time and the scenario. (**bottom two panels**) SLR scenarios are shown for 2020–2100 at Honolulu, Hawai‘i (A), and Apra Harbor, Guam (B; locations noted in the upper-left panel). For information regarding the likelihood of these scenarios under possible future warming levels, see Appendix 3. Figure credit: US Geological Survey, University of Guam, Arizona State University, and NASA Jet Propulsion Laboratory.

## *Increasingly Severe Climate Impacts Are Causing Cascading Impacts for People*

All Pacific Island communities are experiencing climate change impacts and, in some cases, facing existential risks (Figure 30.5). Sea level rise is compromising critical infrastructure and threatens to displace populations on low-lying atolls, forcing migration and disrupting social relationships (KMs 9.1, 9.2, 9.3). The vast majority of ports, airports, primary roads, power plants, and water treatment plants are located a few feet above sea level. Ports bring in 80%–100% of all consumer goods (including food and medical supplies) and 100% of fuel,[67] placing the islands at the end of long supply chains and making them extremely susceptible to disruptions (Ch. 23). Climate change increasingly affects the lands and waters of the region crucial for sustaining primary economic and cultural livelihoods, including tourism, agriculture, fishing, forestry, and artisan practices (KMs 10.2, 18.1, 19.1, 23.2). These effects exacerbate structural inequities (KMs 20.1, 31.2).[68,69] Climate change poses risks to the region's rich biodiversity, including many threatened and endangered species, that supports functioning ecosystems and cultural practices (KMs 8.2, 16.1). Table 30.1 illustrates examples of impacts across the region for each of the chapter's Key Messages related to water and food, human health, the built environment, ecosystems, and cultural and historical resources.

## Climate Change Indicators and Impacts in the Pacific Islands




**Monitoring key indicators of climate change is essential for understanding impacts and informing adaptation efforts.**

**Figure 30.5.** Changes in climate, as measured through key indicators (**top panel**), including sea surface temperature, sea level, and tropical cyclone intensity, result in impacts and risks (**lower panel**) for Pacific Island environments and communities, both on high volcanic islands and atolls. Improved monitoring of indicators is essential for tracking the pace and extent of climate change. Understanding of the connections between indicators and impacts is expanding, which supports adaptation efforts. Adapted from Keener et al. 2018,[26] which was adapted from Keener et al. 2012.[15]

**Table 30.1. Illustrative Climate Change–Related Impacts Across the Pacific Islands Region**

Examples of historical, ongoing, and projected climate change impacts are given for each jurisdiction. Sea level rise is abbreviated as SLR.

| Jurisdiction | KM 30.1: Water and Food | KM 30.2: Human Health | KM 30.3: Built Environment | KM 30.4: Ecosystems | KM 30.5: Cultural and Historical Resources |
|---|---|---|---|---|---|
| American Sāmoa | Increased extreme precipitation events degrade drinking water quality by stressing the water systems' filtration capacity (KM 4.2).[70,71] | Hot weather worsens chronic health conditions, including heart disease and diabetes, already at emergency levels (KM 15.1).[72] | Climate change threatens fisheries and impacts economic infrastructure, including canneries.[73] | Climate change promotes invasive species spread in native rainforests, home to rare and culturally important plants.[29] | Coastal flooding affects villages that contain burials of relatives and ancestors.[74] |
| Commonwealth of the Northern Mariana Islands (CNMI) | Access to safe drinking water is threatened as climate change exacerbates ongoing challenges of disposal of military, industrial, and municipal waste.[27] | Super Typhoon Yutu in 2018 negatively impacted mental health and healthcare providers.[75] | Two successive typhoons (2015 and 2018) damaged or destroyed significant portions of the built environment.[27] | Climate change aids species invasions, which threaten the high biodiversity in wetlands and forests, including endemic birds, threatened reptiles, and two species of bats.[27,76] | Coastal historical and cultural sites are exposed to SLR.[27] |
| Federated States of Micronesia (FSM) | Warmer temperatures and saltwater intrusion are projected to increase disease in staple crops such as taro, bananas, and breadfruit.[77] | Changes to marine and coastal habitats threaten artisanal fisheries, a key protein source.[78,79,80,81,82,83] | In FSM, 59% of infrastructure (89% of population) is within 0.3 miles (0.6 km) of the coast and vulnerable to coastal climate impacts.[84,85] | Highly valued mangrove forests in Pohnpei will be threatened by SLR.[86] | Coastal men's houses *(faluw)* are exposed to SLR and can benefit from historical adaptation measures.[87] |
| Guam | Northern Guam Lens Aquifer is at risk from hotter weather, drought, and possible increases in demand.[28,88] | In 2018–2019, compound extreme events (flash flooding followed by drought and wildfire) negatively impacted human health (safety, pathogens, and respiratory issues).[28] | Stronger tropical cyclones around Guam will increase the potential for severe damage to the built environment.[53] | Increased frequency of coral bleaching[89] and increased risk of wildfires are expected.[28] | Many cultural and historical resources located along the coast will be impacted by 3 feet of SLR.[90] |
| Hawai'i | Increasing drought is reducing available water supplies.[49] | Hot weather causes heat-related illness and increases hospitalizations (KM 15.1).[91] | 3.2 feet of SLR would cause $23.1 billion in economic loss (in 2022 dollars).[92] | Warming at higher elevations will expand transmission of avian malaria, causing declines in endemic bird populations.[93,94] | Strong winds, large storm waves, SLR, and changes in groundwater impact fishponds throughout Hawai'i.[95,96,97] |

| Jurisdiction | KM 30.1: Water and Food | KM 30.2: Human Health | KM 30.3: Built Environment | KM 30.4: Ecosystems | KM 30.5: Cultural and Historical Resources |
|---|---|---|---|---|---|
| Pacific Remote Islands (PRI) | Decreasing precipitation and salinization from SLR are reducing freshwater availability.[98] | The possibility of disappearing islands contributes to distress due to loss of identity and relationship with place (solastalgia).[99] | US military installations and low-lying islets are at risk from SLR, which may impact exclusive economic zones.[98] | The 2014–2016 El Niño bleached over 90% of monitored reefs in Palmyra Atoll.[100] | Sea level rise threatens remote islands and megafauna connected to the Native Hawaiian culture and creation story.[101,102] |
| Republic of the Marshall Islands (RMI) | During the 2015–2016 extreme El Niño drought, the northern atolls established freshwater "filling stations" for water access.[103] | Sea level rise threatens health infrastructure,[104] and migration harms mental health.[105] | Highly urbanized atolls may not be able to adapt to future SLR, leading to land loss and potential uninhabitability.[98,106,107,108] | Tuna catch within the exclusive economic zone is projected to decline by 10%–40% by 2050 relative to the early 2000s under a very high scenario (RCP8.5).[109] | Graves in the Jenrōk neighborhood on Majuro were lost to coastal erosion.[110] |
| Republic of Palau | Climate change affects the timing of when crops are traditionally planted, which impacts food security.[111] | Mental health challenges arise from degradation of places and ecosystems essential to ocean-centered culture and livelihoods (Box 30.3; KM 15.1).[112] | Migration to and development in Koror's coastal zone exposes more people to SLR; king tides already flood urban areas.[113] | The strong 2015–2016 El Niño reduced the jellyfish population in Palau's Jellyfish Lake.[113] | High tides and SLR submerged and damaged Kukau el Bad, a historic healing ritual site in Ollei, Ngarchelong.[113] |

## *Mitigation and Adaptation Through Indigenous Knowledge Systems, Collective Action, and Planning*

Effective climate mitigation and adaptation measures for Pacific Islanders and Indigenous Peoples are grounded in local ecological knowledge, which promotes intergenerational and holistic stewardship approaches,[114,115] and best available Western science (KM 18.3). Indigenous ways of knowing can revitalize resilient practices and confront environmental injustices (KMs 16.3, 31.2).[14] Examples of Indigenous Knowledge–informed adaptation include agroforestry, wetland taro agriculture, fishponds, and fisheries rules such as rest periods.[116,117,118,119] Mangrove and seagrass conservation and regenerative agriculture demonstrate high potential for carbon sequestration (KM 30.4).[120,121,122]

Collective action in the region is codified in pursuit of the Sustainable Development Goals (SDGs) through the Local2030 Islands Network and Micronesia Challenge (Box 30.2; KM 20.2). Climate literacy may help spur collective action and build social capacity to address climate-driven changes (KM 32.5). Climate change–focused education and outreach programming in the Pacific Islands region is diverse and extends across federal, state, and county levels, nongovernmental organizations, and Indigenous-serving organizations (e.g., Bolden et al. 2018;[123] Frungillo et al. 2022;[124] HWMO 2021;[125] Longman et al. 2022;[126] USGS 2021[127]). Native Hawaiian and Pacific Islander epistemologies are woven into many programs (KM 16.2).[128,129]

### Box 30.2. Sustainable Development Goals and Collective Action

Many Pacific Island states have adopted the 17 United Nations Sustainable Development Goals (SDGs)[130] as part of a place-based path toward climate resilience (KM 17.4). The Local2030 Islands Network is forming regional communities of practice around energy, data, tourism, and other topics of interest and is piloting SDG dashboards in Guam, Hawai'i, and Palau (KM 18.4). In Hawai'i, a scorecard provides annual progress summaries on SDGs for 2030.[131] Across sectors, Hawai'i has progressed toward meeting 6 of 36 local SDG metrics as of 2021 and is actively measuring progress in 17 more. While strong progress was made in measuring relevant goals, additional data and efforts are needed to meet more SDGs. Hawai'i Green Growth and Guam Green Growth[132] are diverse public–private partnerships formed to develop measurable economic, social, and environmental adaptations toward sustainability (Box 18.3). FSM's more formal commitment to the SDGs is evident in their national Strategic Development Plan 2004–2023.[133]

The Micronesia Challenge is a commitment by the Commonwealth of the Northern Mariana Islands, the Federated States of Micronesia, Guam, Palau, and the Republic of the Marshall Islands to conserve at least 20% of their terrestrial resources and 30% of their nearshore marine resources. With a regional endowment fund of approximately $23.1 million (in 2022 dollars)[134] providing a sustainable funding stream, the Micronesia Challenge has established over 150 protected areas throughout Micronesia, conserving biodiversity, protecting the environment, securing livelihoods and cultural practices, and enabling these islands to become more resilient to climate change.

## Key Message 30.1

## Climate Change Impairs Access to Healthy Food and Water

Access to clean, fresh water and healthy food is expected to be increasingly impaired by climate change (*very high confidence*). On low-lying atolls, sea level rise has caused saltwater contamination of fresh water (*high confidence*). Regionally, food and water availability will be further negatively impacted by increasing temperatures, altered rainfall patterns, increased flooding and pollution, and degradation of nearshore fisheries (*very high confidence*). Adaptation actions such as traditional farming, fishing, and land-management practices can help build more resilient water and food systems (*very high confidence*).

### *Changing Climate Threatens Freshwater Resources*

Dependable and safe freshwater resources and associated services in tropical islands are particularly vulnerable to rising temperatures (KM 4.1), altered rainfall patterns (Figure 30.3), runoff intensity and flooding, reduced groundwater recharge, and SLR (Figure 30.4; KM 4.2). Depletion of island aquifers compounds the potential for saltwater intrusion from SLR.[98,135,136] The availability of surface water for irrigation, drinking water, and hydropower is affected by increasing frequency and severity of flooding and by reductions in stream baseflow;[137] water contamination through increased *Staphylococcus sp.*, *Leptospira* (a waterborne pathogenic bacteria), fecal coliform bacteria, and suspended sediment (KM 15.1);[138,139,140,141] and extreme drought (KM 2.2).[103] In response to these changes, adaptation-focused restoration techniques are being applied, including revegetating with native species, reducing impervious surfaces, and redundant water distribution systems. Climate-induced land-cover change can have significant control over groundwater recharge, indicating that land-use adaptation is viable for managing impacts on water resources (KM 6.1).[142,143] Flood frequency is projected to increase across the region,[70] while drought frequency is projected to vary across the region (KMs 2.2, 4.1).[27,28,29,113]

#### Changes Undermine the Sustainability of Water Supplies

Pacific Islands potable water supplies depend heavily on accessing clean groundwater or rain catchments, while other needs, such as irrigation, are often met with surface water resources. Groundwater recharge is affected by annual or longer-scale climate processes, while surface water supplies are more sensitive to shorter-term climatic influences.[144,145,146,147,148] Although few studies assess regional changes in drought, evidence is clear that Hawai‘i has experienced a drying trend since the 1950s and in La Niña years.[149,150] On atolls and low-lying islands, freshwater aquifers typically occur as very thin lenses and are highly sensitive to groundwater extraction and SLR-driven saltwater intrusion.[135,136] Shifting rainfall patterns and runoff conditions are affecting the availability of surface water to meet growing demands.[103] Climate change has elevated region-wide efforts to protect and conserve freshwater resources. Communities that rely heavily on rain-fed catchments and surface water are acutely susceptible to short-term and, in particular, long-term drought and the resulting reductions in streamflow.[103]

#### Salinization and Pollutants Deteriorate Water Quality

Increased intensity of extreme rainfall events, coupled with SLR, is projected to exacerbate freshwater contamination risks.[151] Past and ongoing disposal of military, industrial, agricultural, and municipal waste contaminates island water supplies.[35,152] Although SLR-driven mobilization of subsurface contaminants has received little study in the Pacific Islands, evidence of diverse groundwater contaminants in the region[153] and their mobilization[154,155] raises concerns for low-lying island aquifers (KM 4.2). Salt is a critical freshwater contaminant; wave-driven overwash[135,136,156] and SLR-induced rise of the freshwater–saltwater transition zone[157,158,159,160] cause salinization and saltwater intrusion.

Changes in the frequency, severity, and duration of drought, associated fires, and flooding all interact to exacerbate sediment loading to streams.[103,161] Given the short ridge-to-reef distances in the region, sensitive nearshore coral ecosystems and fisheries are directly impacted by increased sediment and pollutant loads to streams,[162] compromising biodiversity, subsistence practices, and economies (KM 9.2).[162,163,164]

## *Food Systems Disrupted*

Climate change will increasingly impact food production, transport, processing, packaging, storage, retail, consumption, and waste for Pacific Island communities (KMs 11.2, 13.1). The aforementioned challenges will disrupt imports reliant on fragile supply chains and reduce viability of local agriculture and fisheries, thus reducing access to nutritious foods.[31,165,166,167,168,169] Fisheries are the principal protein sources for many Pacific Islanders, with locally grown staple food crops such as bananas, taro, breadfruit, and sweet potato supplying critical calories and nutrients.[170,171,172] However, Pacific Island communities have increasingly relied on imported foods, which come with complex and sometimes hidden environmental, financial, social, cultural, and nutritional costs (KM 30.2).[173,174] COVID-19 and previous disasters exposed the fragility of global supply chains (Focus on Risks to Supply Chains) and emphasized the need to bolster local food production capacity to increase resilience.[166,167,175,176]

### Declining Fisheries

The global capacity of coral reefs to supply fish has declined by half since the 1950s, a change that climate stressors have exacerbated (KM 9.2)[62,177,178,179,180] through coral bleaching, acidification, SLR (Figure 30.4), terrestrial sediment, and contaminants (Box 30.3).[78,79,181,182] Small-scale coral reef fisheries supply Pacific Island communities with a substantial portion (in some cases 50% to 90%) of their dietary protein and important micronutrients.[82,172,177,183,184,185,186] Warming waters, acidification, and deoxygenation redistribute open-ocean fish stocks, and fisheries catch within regional EEZs is projected to decline by up to 40% by 2050 relative to the early 2000s under a very high scenario (RCP8.5; KM 10.1).[109] Fishing fleets are ill-equipped to adapt to this deficit (KM 10.2).[81,187] Warming, extreme events, acidification, and SLR may also compromise efforts to expand mariculture (marine farming), through damage to aquaculture systems,[188] decreased species richness,[189] and decreased local access to nearshore and open-ocean species.[190,191,192]

## Box 30.3. Changing Fisheries: Local Knowledge from Palau

Indigenous practitioners are often the first to observe and respond to changes in the environment (KM 16.3). For hundreds of years, fishers in Palau have gathered at seagrass meadows on the sixth day after a new moon during late-afternoon low tide to catch rabbit fish using cast nets (Figure 30.6). Since 2021, fishers have been unable to participate in this age-old tradition.[193] The normal low tide no longer occurs, and ocean levels remain too high for rabbit fish aggregation. It is unclear whether these changes can be attributed to SLR, human impacts (e.g., overfishing), or natural variability. If this change persists, loss of this fishery would threaten the fishers' livelihood and resilience as ocean people (KM 10.2). Integrating place-based and complementary knowledge systems into assessments can help ensure sustainable management under future climate change.[194,195]

### Traditional Cast Net Fishing

**Species loss threatens the traditions, livelihoods, and resilience of Pacific Islanders.**

**Figure 30.6.** Traditional Palauan cast net fishing remains important for local food security. Photo credit: © Reid Endress

## Agriculture

Crop production in the USAPI has generally kept up with population growth over the past 20 years.[165,173] Although local agriculture provides a fraction of nutritional needs in the region,[165] it remains a critical food source, complementing imported foods, serving as an emergency food source, providing culturally important items, and supplementing household income and government revenue.[196,197]

Climate change is projected to impact island food systems through a variety of different mechanisms (KMs 11.1, 23.3).[77] Warmer nighttime temperatures and saltwater intrusion, especially in FSM and RMI, are projected to increase damage from disease on staple crops such as taro, bananas, and breadfruit.[77,198] Cash crops are also *likely* to be affected, with higher temperatures and increased plant pathogens decreasing coffee yields, increased flooding depressing sugar yields, and higher winds damaging coconut palms, bananas, and breadfruit.[191] In Hawai'i, droughts have become longer and more severe and are the principal cause of crop loss.[49]

### Adaptation Strategies to Improve Local Food System Resilience

Strategies are being developed and implemented across the region to revitalize healthier traditional food systems, resulting in more just access to food (KM 11.2).[117,118,165,199] Subsistence-based food system practices such as agroforestry and fishing have sustained Pacific Island peoples for millennia and have aided in recoveries from natural disasters such as typhoons, earthquakes, volcanic eruptions, and tsunamis.[119,171,200,201] Restoring Indigenous agroecology practices can support conservation, food security, and broader sociocultural objectives in the face of shifting precipitation and SLR (e.g., Bremer et al. 2018;[202] Winter et al. 2020[203]). Community food-sharing networks that empowered the most overburdened to overcome economic and social hardship during the COVID-19 pandemic offer a model for resilient food systems in the face of climate change.[175,204,205] Promising fisheries adaptations include establishing networks of marine protected areas to preserve coastal resources, safeguarding fish habitats from pollution runoff, and restoring traditional fishpond mariculture (KM 10.3; e.g., Bell et al. 2013;[73] McLeod et al. 2019;[119] Farmery et al. 2022[116]).

## Box 30.4. Food Security and Traditional Knowledge

For thousands of years, Pacific Islanders have relied on traditional food systems that now face threats from climate change. Traditional agroforestry and aquaculture investments are critical to strengthen food security and reduce reliance on food imports.[4,5,206] The Melai Mai Breadfruit Project was initiated in 2016 to increase food security in typhoon-devastated outer islands of Yap, FSM.[207] Importing diverse breadfruit varieties to extend the harvest length increased food production and sustainability. Other examples include programs working to identify saltwater-tolerant taro species (Figure 30.7) in Palau and distribute them to the community.[111,208]

### Key Agricultural Plants: Giant Swamp Taro

**Programs aimed at supporting traditional crops help strengthen food security.**

**Figure 30.7.** Several varieties of giant swamp taro are salt tolerant, making them valuable for adapting to saltwater intrusion. Photo credit: © Ann Singeo, Ebiil Society Inc.

## Key Message 30.2

## Climate Change Undermines Human Health, but Community Strength Boosts Resilience

Climate change undermines the place-based foundations of human health and well-being in the Pacific Islands (*high confidence*). Climate shocks and stressors compromise healthcare services (*medium confidence*) and worsen long-standing social and economic inequities in both mental and physical health (*high confidence*), and these negative impacts are expected to increase in the future (*very high confidence*). Adaptation efforts that build upon existing community strengths and center local and Indigenous Knowledge systems have great potential to boost resilience (*high confidence*).

Climate change can degrade societal foundations of health and well-being, including access to shelter, nutritious food, clean water, and cultural and social relationships (KM 15.1). Prominent international frameworks and Pacific Island Indigenous conceptualizations of health and well-being recognize that the health of people is closely connected to the health of nonhuman beings, to the shared environment, and to place (Figure 16.3).[209,210,211,212]

Indigenous communities of the Pacific Islands have actively responded to climate-related and other health risks, as well as external economic shocks (Box 30.3; KM 16.3).[119,205] However, colonization and economic disparities have resulted in disproportionately high rates of morbidity and mortality for Native Hawaiian and Indigenous Pacific Island peoples (KM 15.2).[213] Moreover, Pacific Island populations experienced severe economic shocks during the COVID-19 pandemic (KM 30.3),[214] which interacted with existing societal and non-climate stressors that worsen health inequities (KM 18.2).

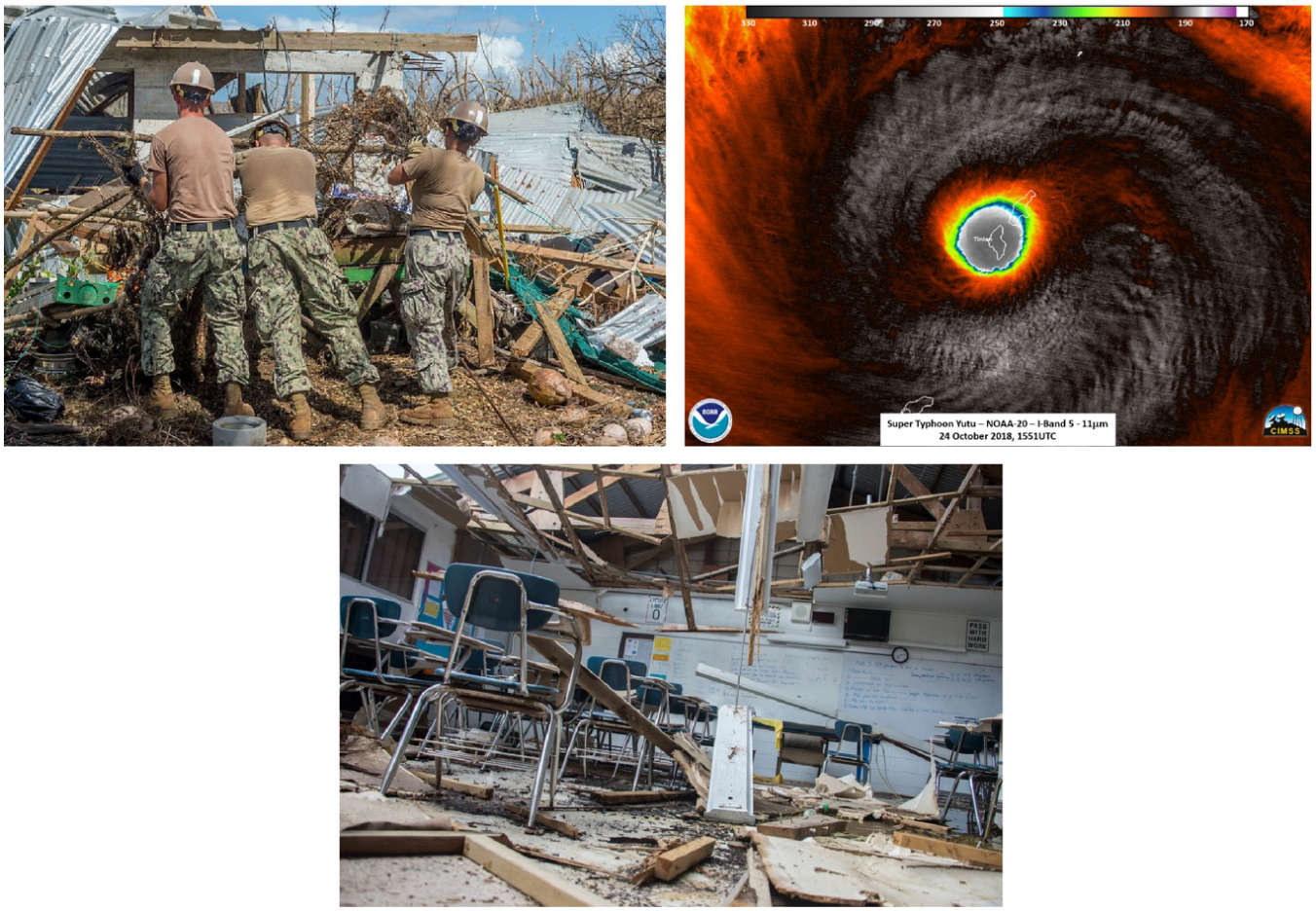
### *The Health Impacts of Extreme Events*

Tropical cyclone intensity,[53,215,216] drought frequency,[150,217] and flood potential (KMs 30.3, 2.2)[70,98,218,219] are expected to increase and continue to aggravate social and geographic inequities (KMs 2.2, 4.2, 10.1, 16.1, 17.4).[53,98] Extreme weather impacts health in ways that persist beyond the initial disaster,[220,221] including increases in food- and waterborne pathogens, loss of access to medications and emergency services, loss of electricity needed for medical equipment and medical facilities, and disruptions to transportation networks, all of which increase illnesses and deaths (KM 15.1).[222] Healthcare facilities in the Pacific Islands are located primarily on coastlines, making them especially susceptible to tropical cyclones and SLR-driven flooding (KM 9.2),[104,223] with limited space and resources for relocation (KM 30.3).

The built environment is especially affected by extreme weather because of high costs of building materials, supply shortages, delays in code updates, and physical isolation (Figure 30.8; KM 30.3).[224] Given the limited emergency infrastructure and evacuation options, extreme weather events create high risks for the mental and physical health of island populations, with individuals with low-income, older adults, children, and persons with disabilities at disproportionately higher risk (Box 15.1).[26,225,226,227]

Drought poses health challenges, particularly for rural island populations. A 2013 drought in the northern atolls of RMI caused crop failures and unsafe and insufficient water supplies, which led to nutritional deficits and increased prevalence of infectious diseases, especially in children.[103,228] Severe wildfires, which occur primarily during droughts,[229,230,231] directly threaten health and safety and can create respiratory hazards (KM 14.2).[232]

## Damage from Typhoon Yutu




**Extreme events acutely affect Pacific Island communities and their built environment.**

**Figure 30.8.** In 2018 Super Typhoon Yutu struck the Commonwealth of the Northern Mariana Islands and damaged or destroyed a significant portion of the islands' buildings and critical infrastructure, leaving a sizable population temporarily unhoused. The experience underscored how events such as cyclones, flooding, and droughts combine with societal factors to acutely affect human health and safety. Images show US Naval personnel clearing debris at a Tinian family's home destroyed by Super Typhoon Yutu (**top left**); a satellite infrared image of Super Typhoon Yutu (**top right**); and a classroom in Hopwood Middle School on Saipan after the storm (**bottom**). Image credits: (top left) Matthew R. White, US Navy; (top right) NOAA/UWM-CIMSS, William Straka III; (bottom) Grace Simoneau, FEMA.

## *Health-Associated Impacts from Migration*

Under a very high scenario (RCP8.5), human migration will increase due to SLR-driven inundation and salinization, displacing people, even entire populations, from low-lying atolls and low-elevation areas of high islands, with enormous implications for health and well-being (KMs 15.1, 17.1, 20.3).[98,105] Migrants often have difficulty navigating foreign healthcare systems[233] and face other barriers to accessing healthcare, including ineligibility for federal programs.[234] An improved understanding of the experiences and health outcomes of people who migrate, within or away from the USAPI, could inform better policy.

## Mental Health Consequences and Climate Grief

Climate change directly and indirectly affects the mental health of Pacific Islanders.[235,236,237] On some islands globally, local climate stressors (such as floods, droughts, and SLR) are linked with negative mental health outcomes such as sadness, distress, and anger (KM 15.1).[238,239,240] Across the Pacific region, studies show that rural populations, socioeconomically disadvantaged groups, and people with disabilities experience more severe mental health consequences from various climate impacts (KM 15.2).[105,239,240,241,242]

Research is limited on the mental health impacts of climate-induced migration. Instability caused by voluntary and involuntary migration is expected to be a continuing source of anxiety,[99] although evidence indicates that social cohesion and reducing disparities can counter negative impacts.[105,243] Some data show that distress from thinking about climate stressors can be comparable to that from experiencing direct impacts.[239] Additionally, because Indigenous People in the Pacific are strongly connected to place, and place is central to conceptions of cultural identity, sudden ecological devastation or gradual change to the environment can create considerable stress (KMs 10.1, 15.1, 15.2, 23.1, 29.1).[99]

Mental health services related to climate change show effectiveness when they are designed to serve Pacific Islander populations in a culturally centered way and include diverse ways of knowing.[235,243,244] Finally, the lack of studies on mental health and climate change in Hawai‘i and the USAPI indicates that additional research may provide a more nuanced understanding of local implications.

## Increase in Vector-Borne Disease

Outbreaks of mosquito-borne diseases such as dengue, chikungunya, and Zika are increasing in frequency, extent, and duration across the region.[245,246] Changes in rainfall (Figure 30.3) and temperature, combined with environmental and demographic changes, are anticipated to exacerbate this trend.[34,247] Resources for vector control and managing outbreaks are limited on small tropical islands, and outbreaks sometimes overwhelm health systems.[245,247] Health officials in FSM, RMI, and Palau are developing predictive modeling to create a dengue early warning system.[248] Similar to how chikungunya and Zika recently emerged and expanded in the Pacific, other vector-borne diseases may emerge in the future.[249]

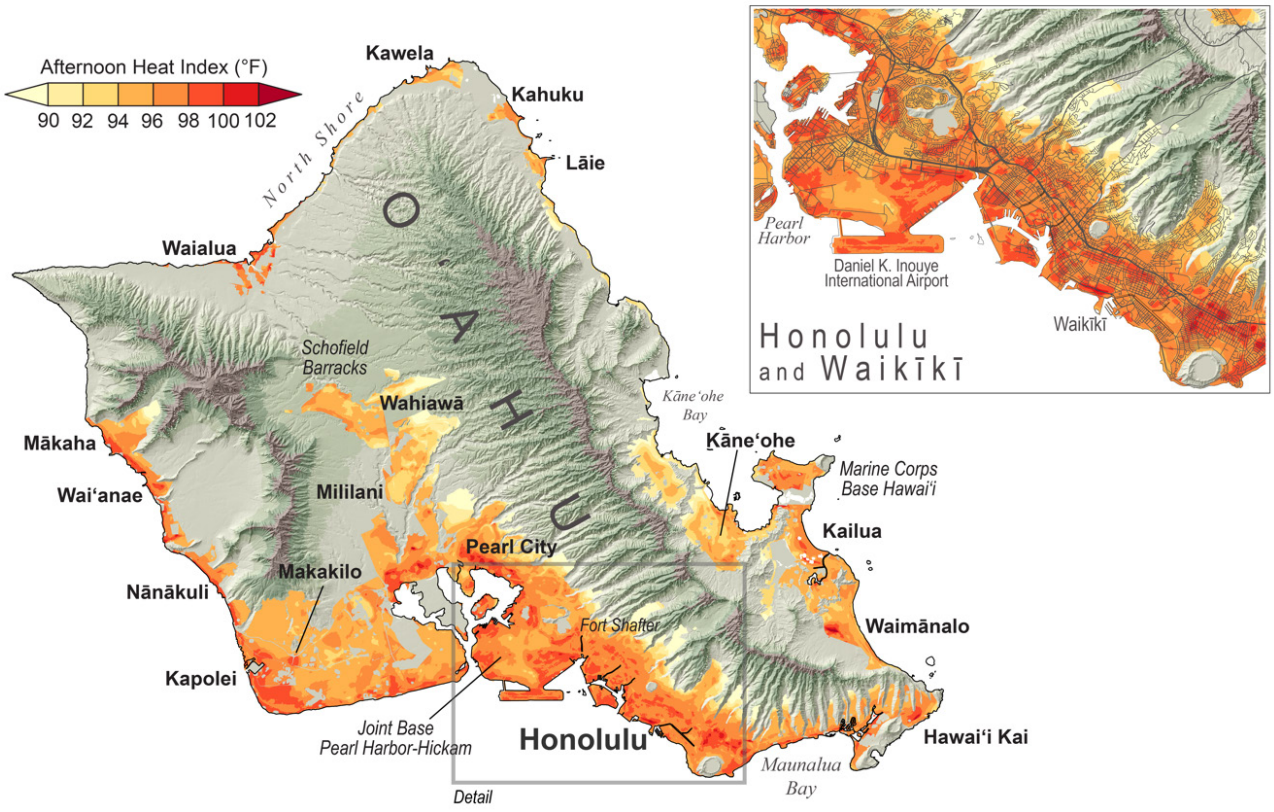
## High Temperatures and Heat-Related Illness and Death

As in much of the US (Figure 2.11), the number of hot days has increased across the Pacific Islands; 2020 was the region's hottest year on record.[27,28,29,45,113] A community heat assessment in O‘ahu, Hawai‘i, in August 2019 found many neighborhoods with record-high afternoon heat indices between 100°F (38°C) and 107°F (42°C) (Figure 30.9).[250,251]

Climate change–driven hot weather causes heat-related illness and increases hospitalizations and deaths; 82% of heat-related deaths in Honolulu are already attributable to climate change (KM 15.1).[252] Those more likely to experience heat-related illness include young children, older adults, outdoor workers, economically burdened and disadvantaged people with little access to cooling or healthcare (KM 15.1), military personnel whose duties require heavy gear and vigorous activity, and non-acclimated visitors.[91] Shock events interact with heat: for example, after the 2009 tsunami in American Sāmoa, dehydration, heat stress illnesses, and barriers to receiving medical care increased.[253]

Imported low-quality foods have replaced local, nutritious, traditional diets (KM 30.1), resulting in some of world's highest prevalence of noncommunicable diseases (NCDs).[165,190,199,254,255] Heat worsens health outcomes for people with NCDs such as heart disease, cancer, stroke, and diabetes[256] and creates challenges for the management of obesity and other diseases because exercise is more difficult to do safely. Overweight and obesity in young children are at a higher prevalence in American Sāmoa, CNMI, and Guam than globally.[257]

## O‘ahu Community Heat Assessment (August 31, 2019)




**High temperatures are responsible for heat-related illnesses, hospitalizations, and death.**

**Figure 30.9.** This community heat assessment map shows the afternoon heat index and “hotspots” for the island of O‘ahu, Hawai‘i. The inset is urban Honolulu. Data were collected by community volunteers and the City and County of Honolulu on August 31, 2019. On this day, the high temperature tied the hottest-ever recorded for Honolulu. Multiple neighborhoods on O‘ahu experienced afternoon heat indices above 100°F (38°C), with a maximum recorded heat index of 107.3°F (42°C). Climate change is increasing the frequency, intensity, and duration of heat extremes, putting individuals and communities at risk. Figure credit: Arizona State University, University of Hawai‘i at Mānoa, NOAA NCEI, and CISESS NC.

## *Social Adaptive Capacity and Community Resilience*

The ability of individuals, communities, and institutions to endure stress and adapt to change determines health impacts of climate change. Recent examples demonstrating the importance of social capital (such as community networks, equitable access to education [KM 15.3], sharing, and relationships) in disaster response include community initiatives addressing flooding on the island of Kaua‘i[258] and drought in RMI.[259] Traditional Knowledge and coping strategies can enhance adaptive capacity and disaster response in some contexts.[260,261,262,263] The resilience of organizations, including health-related institutions and disaster response systems, depends on the ability of organizations to form relationships and communicate with one another, participation by traditional leaders and faith organizations, and effective planning by disaster management agencies (KMs 16.2, 20.2).[227,264,265,266,267] Prioritizing social and mental health initiatives in the health sector would aid in responding to the psychological issues that emerge with disasters and climate change.[268]

## Key Message 30.3

## Rising Sea Levels Threaten Infrastructure and Local Economies and Exacerbate Existing Inequities

Climate change, particularly sea level rise (SLR), will continue to negatively impact the built environment (*very likely*, *high confidence*) and will harm numerous sectors of the islands' economies (*very likely*, *high confidence*). SLR intensifies loss of territory and exclusive economic zones, particularly in low islands (*high confidence*). Climate-driven changes will exacerbate existing social challenges by disrupting livelihoods (*likely*, *medium confidence*). Adaptation to climate change and recovery from disasters is logistically challenging and disproportionately more expensive in the islands (*high confidence*). Government and community groups have developed innovative ways to reduce emissions and improve resilience by moving toward renewable energy and green infrastructure, nature-based urban planning, forward-looking building codes, and sustainable and equitable economic growth, guided by Western science and Traditional Knowledge.

### *Built Environment*

The built environment refers to all human-made structures, including buildings, transportation infrastructure (ports, airports, roads, and bridges), military installations, and distribution systems for food, water, wastewater, communications, and power (electrical, oil, and gas). For this region, it includes traditional structures such as burial grounds, fishponds, and taro terraces (KM 30.5). These structures are critical to connecting people and providing access to goods and services, yet their location within a few feet of sea level renders them particularly vulnerable to SLR (Figure 30.4) and natural disasters (KM 9.2). For example, 98% of RMI's and 80% of Palau's built infrastructure is located within approximately 1,600 feet of their coastlines.[85]

#### Impacts to Infrastructure

Sea level rise will increasingly impact coastal infrastructure through increased magnitude and duration of storm wave–induced flooding (KMs 2.2, 9.1),[98,219,269] rising high tides,[270] and increased coastal erosion (Figure 30.10).[271] In Hawai'i, 3.2 feet of SLR above 2000 levels, which could occur as soon as 2100 under the Intermediate SLR scenario or 2070 under the High scenario (for information on the likelihood of these scenarios, see Appendix 3; Figure 30.4),[65] would affect 550 cultural sites, 38 miles (6%) of major coastal roads, 6,500 structures, and 25,800 acres of land, potentially displacing 20,000 residents and incurring $23.1 billion (in 2022 dollars) in economic loss.[92] Approximately 3 feet of SLR is projected to affect at least 58% of Guam's built environment[90] and most atolls in FSM and RMI.[98] Highly urbanized atolls may not be able to adapt to future SLR (KMs 9.2, 12.2),[106,107] leading to land loss and potential uninhabitability.[98,108] Elevated SSTs can increase bleaching and degradation of coral reefs, which are some islands' primary natural defenses (Figure 30.11; KM 30.4) against coastal flooding.[272] Lastly, increased flooding and erosion due to SLR and stronger future cyclones threaten US military bases in the region, potentially destabilizing regional security and the ability of the Department of Defense to respond to natural disasters (KM 17.1).[53]

## Coastal Flooding Events

**Sea level rise is increasingly impacting infrastructure and communities.**

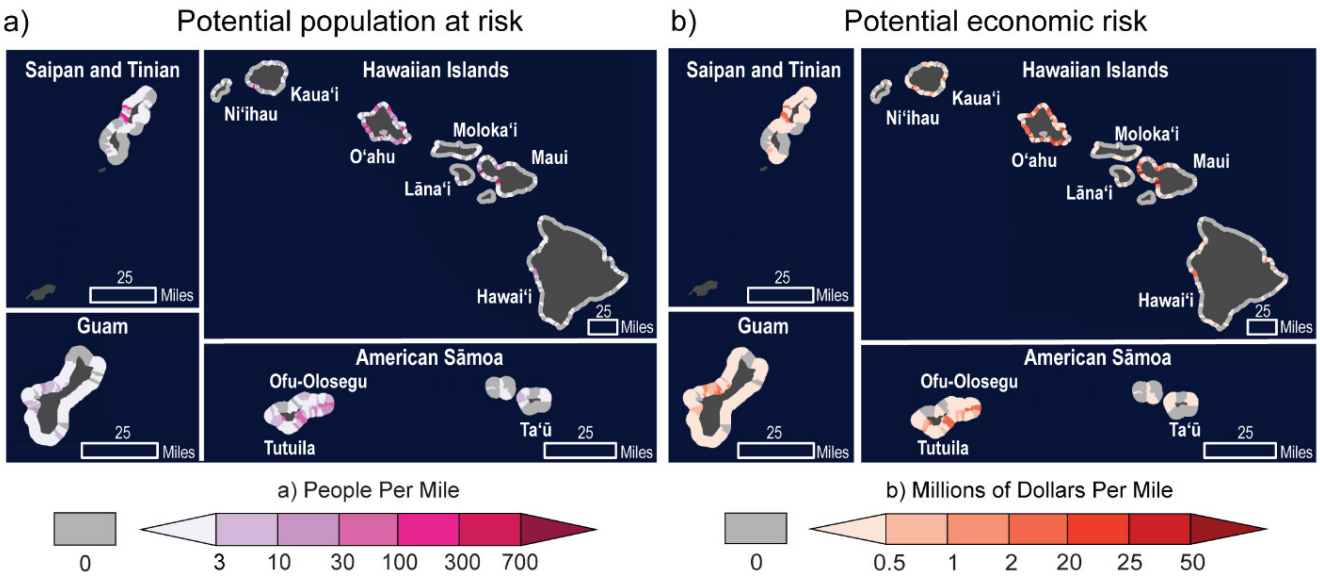
**Figure 30.10.** Rising sea levels are increasing the frequency and magnitude of coastal flooding events. (**top left**) Cars travel through king tide flooding on Oʻahu, Hawaiʻi, in August 2019. (**top right**) High tide inundates a low-lying coastal area in Majuro, Marshall Islands, in February 2020. (**bottom left**) A residence on Oʻahu, Hawaiʻi, has collapsed due to coastal erosion during a large wave event in February 2022. (**bottom right**) American Sāmoa experienced flooding around homes in May 2021. Photo credits: (top left) Maya Walton via © Hawaiʻi Sea Grant King Tides Project, 2019 [CC BY 4.0]; (top right) Max Sudnovsky via © Hawaiʻi Sea Grant King Tides Project, 2020 [CC BY 4.0]; (bottom left) © Shellie Habel; (bottom right) Kelley Anderson Tagarino via © Hawaiʻi Sea Grant King Tides Project, 2021 [CC BY 4.0].

## Adapting the Built Environment

Protecting coastal infrastructure on small islands is costly and requires strong governance and thoughtful urban planning.[273] Hawaiʻi has enacted forward-looking state and county policies, including increased minimum setbacks for coastal development,[274,275,276] setbacks incorporating science-based erosion rates and long-planning horizons that account for future SLR,[275,277,278,279] a first-in-the-Nation mandate to disclose SLR hazards prior to real estate transactions,[280] a requirement for state agencies to assess and plan for SLR impacts,[281] and a mandate that environmental impact assessments consider SLR and other climate factors.[282] While evaluating a balance between public and private property interests (KM 30.5), Hawaiʻi is also assessing the feasibility of relocating some coastal developments,[283] prohibiting most coastal hardening,[274] and helping to preserve public beach access.[283]

Nature-based solutions such as coral reef restoration[284,285] have been proposed at the federal (DARPA Reefense Program),[286] state (e.g., State of Hawai'i 2021[287]), and territorial[288] levels. Such solutions are potentially cost effective for protecting coastal infrastructure[289] and habitats, sustaining ecosystem services such as fisheries (KM 30.1), and supporting tourism and recreation.[290]

### Annual Risk Reduction Benefits Provided by Coral Reefs




**Coral reef degradation could affect thousands of people and cause millions of dollars in damages.**

**Figure 30.11.** The maps show coastal flood protection that the top-most 3.28 feet (1 m) of coral reefs provide annually in American Sāmoa; Guam; Saipan and Tinian (Commonwealth of the Northern Mariana Islands); and Hawai'i. The maps display (**a**) the number of people per mile at risk and (**b**) the potential economic losses (in millions of dollars per mile) from direct building damages and indirect economic disruption from flooding. Adapted from Storlazzi et al. 2019.[291]

## *Livelihoods and Economy*

### Demographics and Migration

Compared to Hawai'i, the USAPI have smaller populations and smaller land masses, as well as fewer financial resources, making adaptation more challenging. During 2010–2020, populations increased in Hawai'i and decreased in American Sāmoa, CNMI, Guam, and Palau.[16,17,18,19,20,21] Pacific Islanders are moving from rural to more urban areas that sometimes lack resources and infrastructure to accommodate influxes of people.[273,292] Migration is a traditional strategy for coping with resource scarcity in Micronesia—for example, a family member often migrates to an urban area for employment, sending money home to support family needs.[293] In 2020, these external remittances accounted for 5.7% of FSM's GDP, 0.08% of Palau's GDP, and 12.7% of RMI's GDP.[294,295,296] As livelihoods in climate-sensitive sectors are impacted by climate change, the amount of money migrants send to relatives will be affected. Climate change may displace populations,[297] but the extent to which climate change drives migration is not well established because migration is an inherent part of Pacific Island cultures.[298] However, some evidence points to a strong correlation between climate impacts on ecosystem services (e.g., food and water provision, protection against floods and storms) and people's propensity to migrate.[299]

## Economy

The costs of adapting to, mitigating, and suffering the consequences of climate change are projected to increase over time, amounting to between 3% and 13% (under the 450ppm and SRES [Special Report on Emission Scenarios] A1FI scenarios, respectively) of Pacific Island regional GDP by 2100 (KM 19.1).[300] Relative to Hawai'i and larger countries, USAPI economies have smaller total GDPs and GDP-per-capita and higher dependence on fisheries and agriculture—climate-sensitive industries representing a large portion of GDP.[301] They also are more dependent on remittances, federal aid, and foreign aid (KM 17.1).[302,303]

Tourism is a major economic engine in the Pacific.[304] Before COVID-19, tourism accounted for over 80% of total exports for Palau and less than 20% for RMI[305] and approximately 25% of total GDP in Hawai'i. Climate change impacts tourism-based jobs and revenue. Damages to the built environment, especially coastal infrastructure, deterioration of natural assets, and expanding vector-borne disease occurrence could reduce tourism.[300]

Fishing is a critical economic sector in many Pacific Islands.[178,306] Tuna license revenues represent a significant source of government income for the FAS but are expected to decline due to projected changes in fish availability in the EEZs (KMs 10.1, 10.2),[79,80,81,83,306] with ramifications for local canneries in American Sāmoa and the FAS. Changing coastlines and potential land loss from SLR may result in changed maritime entitlements via changes in the size and shape of the respective EEZs,[306] affecting not just fisheries but also marine mineral rights. Climate-related marine and coastal habitat impacts threaten artisanal fisheries, a critical source of food and income for many households (KMs 30.1, 10.1, 10.2).[78,82,178,184]

## Estimated Economic Costs of Climate Change

The estimated economic impacts of climate change will vary by sector. Coastal hazards have a disproportionately large impact on small islands' GDPs.[307] Specifically, the projected increased duration and magnitude of storm wave–induced flooding[98,219,269] and increased coastal erosion[271] can damage infrastructure underpinning the local economy. Degradation of coral reefs due to a rise in SSTs[272] could incur coastal damages costing approximately $1.2 billion (in 2022 dollars) annually to the economies of Hawai'i and the US Pacific territories.[218]

In American Sāmoa and Guam, coastal flooding and erosion are projected to disproportionately harm at-risk individuals, including minority and low-income populations and those younger than 16 or older than 65 (groups defined by the 2010 US Census data).[218] High-risk coastal properties (i.e., those located in hazard-erosion areas of updated FEMA Flood Insurance Rate Maps) will be difficult to insure.[308] Increased coastal flooding events and drought are expected to negatively impact agricultural revenues (KM 30.1). For example, between 2008 and 2016, Hawai'i lost approximately $53.5 million (in 2022 dollars) in cattle production due to the most severe drought on record, and federal crop insurance programs paid $11.2 million (in 2022 dollars) to farmers for drought losses during 1996–2018, mainly for macadamia nuts and coffee.[49]

## Adapting Livelihoods and Economies

As a percentage of GDP, the costs of climate change adaptation are significantly higher for small islands than for larger countries.[300,309] Islands' geographic isolation, reliance on imported goods, and vulnerable infrastructure can increase adaptation and disaster recovery costs (see Figure 30.8).[224] Hawai'i and the USAPI have adopted the United Nations Sustainable Development Goals (Box 30.2)[130] to increase resilience by creating more equitable approaches to adaptation and mitigation. Financing costly climate adaptation is a shared international challenge for the FAS (KM 17.4).[300,301] Unlike American Sāmoa, CNMI, Guam, and Hawai'i, the sovereign FAS are eligible for foreign direct investment and receive substantial funding from the Green Climate Fund,[310] the Asian Development Bank,[311,312] the US Government via the Compact of Free Association,[310,313] and other nations (KMs 19.2, 19.3).[314] Because credit agencies are increasingly considering

vulnerability to climate change as a factor in their ratings, however, Palau's and RMI's credit ratings may decrease, with negative impacts on their abilities to borrow external funds, attract foreign investment, or access below-market-rate financing to accelerate development.[315]

## Decarbonization, Sequestration, and Resilience

Although many Pacific Islands emit minimal greenhouse gases, they are striving to reduce emissions and sequester carbon while addressing ecosystem resilience needs.[119] For example, Guam and Hawai'i established 100% renewable portfolio standards for the electricity sector, to be achieved by no later than 2045.[316,317] Hawai'i established a net-negative emissions target by 2045 and created a sequestration task force[282] charged with establishing baselines and benchmarks, recommending policies including mitigation, and developing strategies for sustainable agriculture. This work led to a carbon pricing evaluation.[318] Similarly, RMI pledged emissions reductions of 45% below 2010 levels by 2030 and carbon neutrality by 2050.[319] Palau recently committed to 100% energy generation from renewable sources by 2032.[320] Opportunities exist for ecosystem-based, place-based adaptation and mitigation informed by Indigenous Knowledge systems (KMs 30.1, 30.5).[321,322,323]

With limited land areas, each island in the region is carefully evaluating options for transitioning to renewable energy. In 2016, American Sāmoa's island of Ta'ū transitioned its energy supply from 100% diesel to 100% solar with battery backup.[324] In Hawai'i, rapid growth of rooftop solar generation—combined with centralized solar, battery storage, wind power, and pumped hydropower storage—is enabling a transition away from an oil-predominant grid.[325] The potential for success is high: Kaua'i's grid achieved a 69.5% renewable portfolio standard in 2021, and the island is occasionally 100% renewably powered during midday hours; it is projected to achieve a 90% renewable portfolio by 2026.[326,327] Hawai'i's Act 100[328] required a community-based renewable energy program; power utilities and communities in the region are now developing mechanisms to enable shared ownership of renewable infrastructure.[329]

## Key Message 30.4

## Responses to Rising Threats May Help Safeguard Tropical Ecosystems and Biodiversity

The structure and composition of Pacific Island coastal and marine ecological communities are directly threatened by rising ocean temperatures, ocean acidification, and sea level rise (*very likely*, *high confidence*). Increasingly severe droughts and warming are increasing fire risk (*high confidence*) and will have broad negative impacts on native plants and wildlife, including an increased risk of forest bird extinctions (*very likely*, *high confidence*). Adaptation strategies improve the resilience of ecosystems, including ecosystem protection, ecological restoration, invasive species prevention and control, and investments in fire prevention (*medium confidence*).

### *Marine and Coastal Ecosystems*

Pacific Island marine environments serve as the foundation for local food systems and cultures (Figure 30.12). Rising ocean temperatures, declining dissolved oxygen concentrations, and marine heatwaves are projected to impact the structure and composition of marine ecosystems (Figure 30.5; Ch. 8; KM 10.1).[330] Global marine food web models project biomass declines of 10% to 40% across the region throughout this century, with greater declines projected for large predators.[331] Finally, marine species within the region's EEZs are projected to shift beyond historical ranges as early as 2030—sooner than much of the globe.[83]

Coastal and oceanic environments supply direct goods and services such as fish, recreation and tourism areas, regulating services such as coastal protection and carbon storage, and means for trade and transportation—collectively valued at over $3.1 trillion per year (in 2022 dollars; KM 23.2).[332] Rising SSTs and marine heatwaves continue to be the most pressing climate change impacts facing Pacific reefs,[333,334] leading to more frequent and severe bleaching events with less recovery time.[61,62,335,336] Bleaching-induced mortality has reduced coral cover and decreased available habitat for reef-associated species.[62,334] Increased SSTs will negatively affect some animal species distributions,[337,338,339] and rising ocean and sand temperatures lead to a higher ratio of female sea turtles observed around the Pacific, threatening the viability of sea turtle populations.[340] Increased air temperatures and reduced precipitation are *likely* to have negative effects on coastal vegetation[341] and coastal pond communities,[342] adversely affecting coral reefs, seagrasses, and mangroves via altered sediment and pollutant delivery to coasts.[343] Increased ocean acidity[344] and increased nutrient runoff from the land[345] negatively impact corals, shellfish, and associated fisheries (KM 30.1). Although these systems generally have limited capacity to adapt to large climatic changes, regional strategies are being developed to reduce impacts.[337,338,346]

## Box 30.5. Blue Carbon Ecosystems

USAPI mangroves and seagrasses are among the world's most productive blue carbon ecosystems (BCEs—ocean and coastal ecosystems that capture carbon; Focus on Blue Carbon),[347] storing over 30% of total island carbon despite their small area.[120] Guam, the Republic of the Marshall Islands, the Federated States of Micronesia, and Palau plan to use BCE carbon to offset emissions while also protecting coastal infrastructure.[285,348,349] BCEs also provide food, fiber, fuel, and income to Pacific Islanders.[350] Mangroves are non-native to Hawai'i and threaten shorebird habitat, coastal access, and cultural sites and services.[351] However, evidence suggests that these non-native species can provide some ecosystem benefits, for example, by significantly increasing coastal sediment accumulation[352] and carbon capture rates.[353] Mangrove loss in Micronesia is projected to start by 2080 under Intermediate SLR scenarios (Figure 30.4).[86] The conservation and restoration of BCEs and their associated reef systems provide cost-effective solutions for protecting coastal communities and increasing other benefits (KM 8.3).[289]

Sea level rise will cause more frequent and extensive flooding of coastal ecosystems, impacting plants[354,355] and animals,[356] especially on low-lying atolls such as those in the Northwestern Hawaiian Islands, PRI, RMI, and FSM. In some cases, flooding is *likely* to increase erosion rates, reducing the elevation of mangroves, vegetated dunes, and beaches. Development exacerbates these drivers by exposing soils, creating impervious surfaces, and impeding inland migration of coastal ecosystems, limiting their adaptive capacity.[357]

### Characteristic Ecosystems of the Pacific Islands

**Pacific Island marine environments provide the foundation for local food systems and cultures.**

**Figure 30.12.** Pacific Islands offer a diversity of ecosystems that include mangroves (**top left**), limestone forests (**bottom left**), tropical alpine habitats (**top center**), dry forests (**bottom center**), coral reefs (**top right**), and cloud forests (**bottom right**). Photo credits: (top left) Richard Mackenzie, USDA Forest Service; (top center) © Paul Krushelnycky, University of Hawai'i; (top right) © Underwater Earth / XL Catlin Seaview Survey / Christophe Bailhache; (bottom left) Christian Giardina, USDA Forest Service; (bottom center) Hawai'i Department of Land and Natural Resources; (bottom right) Lucas Fortini, USGS.

## *High Island Ecosystems*

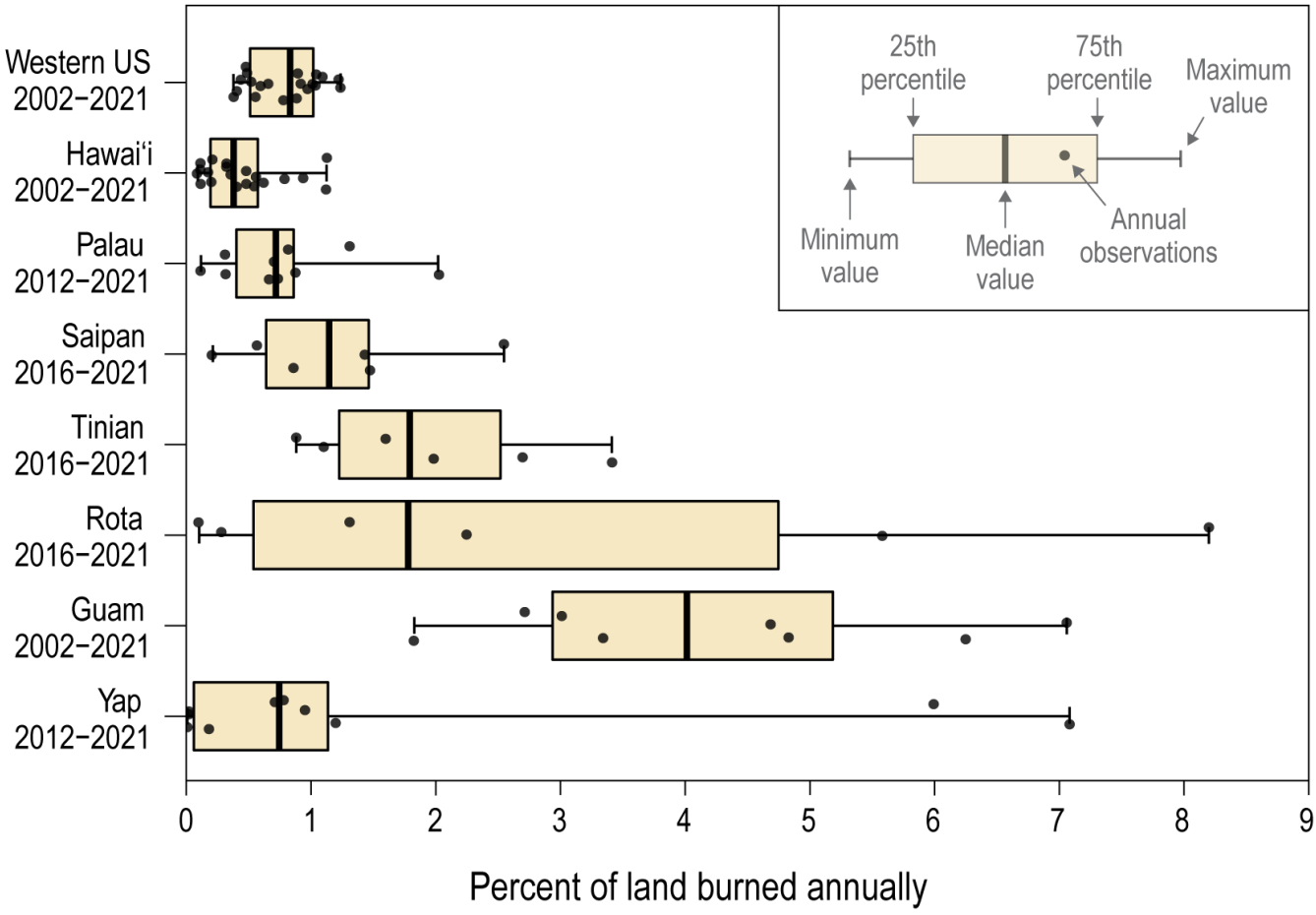
Terrestrial ecosystems of high islands (i.e., islands characterized by volcanic origin and consequently more diverse topography) have evolved in isolation from continental areas, resulting in unique and diverse fauna and flora with a high proportion of native species naturally occurring only on these islands (Figure 30.12). However, the combination of invasive plants and animals and diseases; habitat destruction; and intensifying fire regimes and ecological drought has resulted in severe range contractions and native species extinctions.[93,358,359,360,361,362,363]

In Hawai'i, past droughts and rainfall variability had landscape-level impacts on vegetation[364,365] and cascading ecological effects.[366] Long-term climatic shifts are *likely* to accelerate range contraction and extinction rates,[93,367] but responses will vary by species, including differences in drought tolerance across populations.[368,369,370,371]

Rainfall changes (Figure 30.3) will affect island aquatic ecosystems. In Hawai'i, declines in dry-season streamflow will result in more intermittent streams[137] and loss of habitat connectivity and conservation value.[372] Decreased streamflow will also negatively impact stream organisms by reducing fitness and increasing disease and habitat for invasive fish and mosquitoes.[373,374,375]

Across the region, climatic shifts are expected to impact native ecosystems via interactions with fire (e.g., Trauernicht 2019;[376] Nugent et al. 2020[377]). Wildland fires already burn a higher proportion of total land area in the Pacific Islands than in the continental US (Figure 30.13)[229,378] and are strongly linked to El Niño events.[49,103] While limited future climate projections indicate increasing fire probabilities,[376] the future of fire in the region is highly sensitive to management and policy decisions, since ignitions are largely caused by humans (e.g., Dendy et al. 2022;[229] Trauernicht et al. 2015[378]). Education and outreach will continue to play a critical role in wildfire mitigation (e.g., HWMO 2021[125]).

### Wildfire Area Burned in the Pacific Islands Compared to the Western US




**Wildfires burn large percentages of land in Pacific Islands compared to the western US.**

**Figure 30.13.** The annual percentage of total land area burned for seven Pacific Islands is equivalent to or greater than the percent area burned for western US states. Years examined are noted for each location. Figure credit: USDA Forest Service, USGS, NOAA NCEI, and CISESS NC.

Interactions between invasive species and climate change in isolated Pacific Islands are complex (KM 8.2),[379,380,381,382,383] with climate change most often exacerbating invasion.[384,385,386,387] Invasive species may aggravate local water stress, for instance, by using more water resources than native plants[148,380,388,389] or by causing less rainfall to reach the forest floor, as in the case of strawberry guava invasion.[148,390] Similarly, fire-prone invasive vegetation is likely to further increase future climate-driven fire risk.[376] With the steep increase in the number of naturalized species on Pacific Islands,[391] these climate and invasion interactions will become increasingly important for managers to address.[392] Critical region-wide investments are being made to prevent the introduction of potentially invasive species and diseases,[393] given that climate change can alter pathways for species introductions.[394,395,396]

## *Responding to Rising Threats*

Regional efforts increasingly focus on restoration management that enhances climate resilience.[397,398,399,400,401] Besides boosting adaptive capacity,[402] ecosystem restoration efforts may provide multiple benefits to islands, including hydrological (KM 8.3)[140,148,161,401,403,404] and sociocultural benefits,[404,405] as well as carbon sequestration[406] and sediment retention.[407] Hawai'i and the USAPI have established both marine and terrestrial protected areas (Box 30.2),[119,134,408,409] which elsewhere have successfully supported ecosystem resilience

under climate change (e.g., Gaüzère et al. 2016;[410] Lawler and Hepinstall-Cymerman 2010;[411] Roberts et al 2017;[412] Virkkala et al. 2014[413]).

The urgency of conservation actions (Figure 30.14) is exemplified by the Hawaiian forest bird crisis. Forest bird populations are declining due to avian malaria spread driven by warming.[414,415] Managers are exploring options for safeguarding species near extinction,[416,417,418,419] including habitat restoration, avian malaria vector control,[420] and translocation.[421,422,423,424]

In addressing these myriad challenges, conservation efforts increasingly involve broader partnerships with educators (e.g., Bolden et al. 2018[123]) and Indigenous Knowledge holders, who play a vital role in conservation planning and implementation (KM 30.5; Ch. 16).[405,425,426,427,428]

## The Climate Urgency of Pacific Island Conservation

**Conservation efforts across the region help to restore ecosystem health and protect native species.**

**Figure 30.14.** These images depict on-the-ground climate-related conservation actions across Pacific Island ecosystems: wildfire management in Hawai'i Volcanoes National Park (**top left**); planting native species in Palau to restore watershed health (**bottom left**); installing protective fencing around native habitat in Hawai'i (**bottom center**); conservation of native snails using captive populations to prevent extinction of vulnerable populations (**top right**); seabird translocations in the Northwestern Hawaiian Islands to safeguard against sea level rise (**center right**); and climate-resilient coral reef restoration experiments in Hawai'i (**bottom right**). Photo credits: (top left) D. Benitiez, NPS; (top right) © Chris A. Johns; (center right) © Lindsay Young, Pacific Rim Conservation; (bottom left) © Ann Singeo, Ebiil Society Inc.; (bottom center) NPS; (bottom right) Hawai'i Department of Land and Natural Resources.

## Key Message 30.5

## Indigenous Knowledge Systems Strengthen Island Resilience

Indigenous Peoples and their knowledge systems are central to the resilience of island communities amidst the changing climate (*high confidence*). Reciprocal and spiritual relationships among the lands, territories, waters, resources, and peoples are being strengthened and sustained as communities adapt and manage their resources collectively (*high confidence*). Indigenous Peoples are identifying and quantifying the potential loss and migration of critical resources and expanding the cultivation of traditional food crops on high islands (*high confidence*).

### *Reciprocal Relationships Between People and Place*

Communities throughout Hawai'i and the USAPI demonstrate Indigenous cultural and community resilience grounded in Traditional Knowledge as they continue to adapt to global changes, just as their ancestors have for millennia (KM 18.3; Figure 16.3).[87] These adaptations and the collective resilience of Indigenous communities are strengthened and sustained through reciprocal exchanges between the peoples and the lands, territories, waters, and resources to which they are genealogically connected (Figure 30.15). Resilient communities are vital to the overall health and well-being of island peoples. To effectively advance the science of sustainability and manage resources amidst the changing climate, spiritual rituals and engagements are central to biocultural well-being—the collective well-being of landscapes, seascapes, and Indigenous communities (Box 30.6).[429] Through these rituals and engagements, island communities individually and collectively are able to connect to the place and all of its life-forms, cultivating reciprocal relations that enhance future resource abundance based on responsibility rather than ownership.[430]

#### Restoring and Caring for Hawaiian Limu (Seaweed)

**The resilience of Pacific Island communities is strengthened by their connection to place and all of its life-forms.**

**Figure 30.15.** *Limu* refers to ocean plants, including seaweed. The governor of Hawai'i designated 2022 as the Year of the Limu as a part of a statewide community effort to raise awareness about the importance of limu to Hawai'i's cultural identity and the health of the nearshore marine environment. The KUA Limu Hui (a seaweed practitioners group) shares traditional knowledge and practices related to limu gathering, use, and restoration. *Limu kala* (*Sargassum echinocarpum*; **left**) is incorporated into various food dishes, is used as bait for reef fish, and is an important component in Hawaiian forgiveness ceremonies. Limu such as *palahalaha* (*Ulva fasciata*; **right**) also play a critical role in intertidal ecosystems as they provide food and shelter for invertebrates and herbivores. Photo credits: © Haunani Kane.

## Box 30.6. Local Cultural Resilience to Climate Change

Communities across the region are working to build local cultural resilience to climate change. In Hawai'i, community-based subsistence fishing[431] and forest[432] areas were established as place-based approaches to strengthen communities' ability to formally manage their natural resources through traditional and customary skills, practices, and social networks. Communities are cultivating reciprocal relationships as a shared responsibility[433] and including sacred relationships and ritual approaches to land and sea stewardship.[429] In Hawai'i, a common practice within the community is to ask for permission to physically and spiritually enter a sacred space, as this allows community members to introduce their genealogies to the lands and people, as well as express gratitude and respect for the land—the elder sibling—to sustain future generations.

### *Cultural and Historical Sites*

Archaeological, cultural, and historical sites are representations of the living culture and ancestral knowledge of Indigenous and island peoples, and they serve as potential resources and models as communities seek to remediate increasing climate risks and impacts (Figure 30.16).[87,118,119,434] Indigenous communities are identifying and protecting cultural and historical sites, assessing climate impacts on natural resources, and creating restoration plans (KM 16.3).[435,436]

Archaeological sites and oral history document the culturally grounded and traditional resilience of island peoples to historical coastal change that resulted from extreme events and higher sea levels. Approximately 2,000–4,000 years ago across the equatorial Pacific, sea level was at least 3.3–6.6 feet higher than present, which directly influenced the timing of atoll formation and the initial migrations and settlement of island people.[437] Initial settlers of Majuro atoll, RMI, arrived within 100 years of island formation, when sea level was 3.3 feet higher than present, and they cultivated trees and shrubs into crop systems rather than waiting for natural vegetation succession.[438] On Yap, FSM, coastal stone-built structures are expressions of innovation, cultural identity, and pride that allowed islanders to occupy coastal areas under elevated sea level, and modern structures such as the coastal men's houses (*faluw*) and taro gardens document cultural resistance to rising waters.[87] On Guam, traditional CHamoru houses were elevated on limestone pillars (*latte*) along the coast, protecting them from coastal inundation.[439] Across higher islands like Sāmoa, settlement along narrow coastal plains occurred after nearly 1,000 years of sea level fall and subsequent natural development of habitable coastal environments.[437] The oral histories, stories, myths, storyboards (Palau), and songs/chants of Indigenous Peoples record their observations of the changing environments and lifestyles. The proverb *He pūko'a kani 'āina* describes the natural evolution of a coral reef into an island and is also interpreted by Native Hawaiians to describe the resilience of a person who begins in a small way and gains steadily until she becomes firmly established.[440]

### Climate Change Impacts on Cultural Sites

**Cultural sites, representing the living culture and ancestral knowledge of Indigenous Peoples, are at increasing risk.**

**Figure 30.16.** Sea level rise (SLR), strong winds, and large storm waves impact a fishpond in Kaloko-Honokōhau, Hawai'i (**left**). Kukau El Bad, a cultural site in Ngarchelong State, Palau, is inundated by salt water and continues to be threatened by SLR, storm surge, and erosion (**right**). Photo credits: (left) © Kimberly Crawford; (right) © Ann Singeo, Ebiil Society Inc.

Across the region, one approach to mediating climate impacts is to reinvigorate and restore food production across landscapes (KMs 11.1, 30.1; Box 30.4).[441] This is being accomplished through several pathways. At a policy level, work is being done to amend law in Hawai'i to add a "Traditional Lands" zone under the state's Land Use Commission that would streamline permit and building requirements[194] for eco-village-type living with mixed-use housing and other sustainable infrastructure such as commercial kitchen and food-processing facilities, as well as the use of traditional agriculture lands such as *lo'i kalo* (irrigated taro, agriculture), *loko i'a* (fishponds), and large expanses used to traditionally farm staple crops such as *'uala* (sweet potato).[442] Communities and cultural practitioners are working with scientists to identify areas where food production could be expanded under future climate scenarios (KM 12.4). For example, taro cultivation was modeled under future SLR scenarios[434] and sweet potato[442] and breadfruit under increasing temperature and rainfall scenarios,[118] showing the potential resilience of these traditional agricultural practices.

## *Indigenous Knowledge Systems and Values of Ecosystem Services*

Indigenous island communities are also working to ensure that Traditional Knowledge is central to resilience strategies (KM 16.3). A growing body of Indigenous-led research describes how biocultural methods can successfully be incorporated into efforts focused on community-based subsistence,[431,432] relationships to place,[433] cultural–ecosystem service assessments,[443] and the protection of historical and cultural resources.[444] Biocultural approaches start with and build upon local cultural perspectives by encompassing values, knowledge, and needs and by recognizing reciprocal restoration between ecosystems and human well-being (KM 20.3).[195,443] The act of restoring ecosystem services contributes to cultural revitalization[433] by reaffirming connection to place, enhancing community relationships and social networks and the physical and mental well-being of Indigenous Peoples,[405] increasing local food production,[202] and diversifying the local economy[427]—all while distributing the abundance through reciprocal exchange.[431] In return, the renewal of culture promotes the restoration of ecological integrity through the creation and expansion of habitat for native species[434] and further supports recovery and resilience of ecosystems following future environmental disturbances (KM 8.3).[445] Equitable outcomes from climate research and planning are predicated on properly citing Indigenous elders and knowledge keepers,[446] enhancing Indigenous control of Indigenous data via data sovereignty, protecting intellectual property rights, and establishing free, prior, and informed consent (KMs 16.2, 20.2, 31.2).[447,448]

# Traceable Accounts

## *Process Description*

To build the author team, the federal coordinating lead author and the regional chapter lead author utilized the Fourth National Climate Assessment (NCA4) Key Messages and their assessment of new emerging issues to select key sectors of importance to the region. The lead authors compiled a comprehensive list of potential authors with expertise in those sectors. The regional chapter lead author then selected a total of 14 authors to join the team, representing a wide range of geographical and technical expertise (including physical and social scientists as well as cultural practitioners) and a diversity of career stages, affiliations (federal, academic, and private), and previous assessment experience.

The author team met weekly (virtually) to discuss chapter content and plan engagement activities. After brainstorming and agreeing on the five key topic areas for the chapter, authors identified which sections they would contribute to and met regularly in subgroups to discuss content. The team held a virtual public engagement workshop on January 24, 2022, to solicit public feedback on the chapter outline. In addition, the author team held five virtual technical meetings (one for each topic) where technical experts were invited to brainstorm and collect information to ensure the chapter covered the latest scientific results and most important topics in the region. The author team utilized interactive engagement tools to facilitate meetings, including collaborative writing exercises. Participants who contributed significantly to shaping chapter content were invited as technical contributors. Inputs from the workshop and technical meetings were synthesized by the author team and incorporated into the chapter draft.

Throughout this chapter, future projections of the physical environment come from general circulation models and earth system models from the fifth and sixth Coupled Model Intercomparison Projects (CMIP5[449] and CMIP6[450]).

## Key Message 30.1

## Climate Change Impairs Access to Healthy Food and Water

### Description of Evidence Base

Global assessments support findings that coastal land loss attributable to sea level rise (SLR), increased precipitation, wave impacts, and increased aridity drive food and water insecurity on small islands.[89] Regional literature shows decreasing water quality and food production in both observed trends and modeled projections (KM 11.1).[77,135,147] However, these climate change manifestations are highly variable across different islands and within islands. Limited studies (e.g., Denton et al. 2014;[152] Felton 2021;[151] Ghazal et al. 2019;[144] Jarsjö et al. 2020;[154] Kibria et al. 2021;[155] Leta et al. 2017,[145] 2018;[146] Mair et al. 2019;[147] Strauch et al. 2014,[140] 2015,[451] 2018[141]) have quantified these effects on water resources and water quality throughout the large and diverse region. Although available studies and their results may be applicable to other, understudied islands, given the high diversity among islands, additional site-specific assessments in the Pacific Islands region would improve understanding of the impacts of climate change on water.

The importance of fisheries and agriculture for nutrition and livelihoods, and the nexus between food, trade, and malnutrition, come from a well-established evidence base,[31,32,165,175,191,199,255,452,453] although localized assessments dissecting socioeconomic–ecological dynamics remain limited.[166,199] Clear evidence shows that local agricultural and fisheries production is not keeping up with population, with outputs falling due to climate change.[31,452,454]

It is clear that fish, and particularly reef fish, are essential for regional nutrition and food security.[82,177,183] Evidence indicates that climate change is driving and will continue to drive changes to coral reefs and fisheries yields (along with pollution and overharvest).[78,81,113]

A broad literature base clearly establishes strong connections between drought and water security, sanitation, food productivity, and increased risk of wildfires.[191,217] Although few studies assess regional changes in drought,[49,50] Hawai'i has clearly experienced a drying trend,[48] particularly since the 1950s in La Niña years.[149,150]

It is generally agreed that reinvigorating local agricultural and marine food systems will be necessary, but not sufficient, for food security[116,175,190] and that investment in climate-resilient food supply chains is needed.[166,167,176]

## Major Uncertainties and Research Gaps

Global and downscaled projections of rainfall exhibit large uncertainty in direction and magnitude of future change (e.g., Elison Timm et al. 2015;[51] Xue et al. 2020;[455] Zhang et al. 2016[57]). Island-specific downscaled projections of hydrometeorological extremes (drought, flooding, heavy precipitation) are not currently available for Hawai'i or the US-Affiliated Pacific Islands (USAPI). Understanding of future groundwater availability is limited by the lack of island-specific groundwater models for islands outside of the main Hawaiian Islands, some atolls in the Federated States of Micronesia, and Guam (e.g., Bailey et al. 2008;[456] Gingerich 2013;[457] Izuka et al. 2021[458]). Very little research exists regarding enhanced mobilization of subsurface contaminants from rising sea levels, despite the existence of many coastal contamination sites. Watershed management could be improved through better understanding of the current impacts of invasive plants (e.g., strawberry guava, *Psidium cattleianum*) on evapotranspiration and water cycling, and of how future climate change will modify such impacts.

Localized food supply chain vulnerability assessments are lacking (e.g., Dyer 2018[32]). Salt tolerance in many key agricultural plants is still not well understood (e.g., Palanivel and Shah 2021[198]), nor are the interactions between climate change and invasive agricultural pests. Reliable fish consumption information is not disaggregated by socioeconomic demographics nor by fish type, precluding analysis of nutrition (and risk from contaminants) by group. Barriers to and opportunities for reinvigorating local food systems are localized and require further analysis.

## Description of Confidence and Likelihood

There is *very high confidence* that climate change will impair future access to clean and fresh water and healthy food. Broad global and regional literature support the finding that future water access will be compromised by reduced water availability, compromised water quality (KMs 2.2, 4.1),[26,103,138,139,140] and saltwater contamination, which has already been exacerbated by SLR, especially on atolls (*high confidence*).[98,135,136] The literature agrees that climate change will disrupt global food imports and supply chains through declines in nearshore and open-ocean fish stocks in the Pacific,[31,81,109,165,166,167,168,169,177,178,179] increased crop disease,[77,191] and drought.[49,103]

There is *very high confidence* that food and water availability will be negatively impacted by increasing temperatures, altered rainfall, flooding, pollution, and fisheries degradation. This confidence assessment is demonstrated by numerous peer-reviewed studies, robust global climate projections, and observations of changes to crop yields, fisheries, and freshwater ecosystems (e.g., Frazier et al. 2019;[103] Ghazal et al. 2019;[144] Leta et al. 2017,[145] 2018;[146] Mair et al. 2019;[147] Strauch et al. 2014,[140] 2015,[451] 2018[141]). Based on a broad evidence base including peer-reviewed literature and Indigenous Knowledge, there is *very high confidence* that adaptation actions such as traditional farming, fishing, and land management practices can help build more resilient water and food systems.[73,116,119,175,194,195,202,203,204,205]

## Key Message 30.2

## Climate Change Undermines Human Health, but Community Strength Boosts Resilience

### Description of Evidence Base

Multiple assessments find an increasing trend in people affected or killed by climate-related disasters and extreme weather events worldwide.[220,221] While health infrastructure exposure to climate risk is well documented globally, few vulnerability assessments for islands, territories, and states in the Pacific (e.g., Greene and Skeele 2014[223]) have examined health infrastructure vulnerability. Just one study of medical facility vulnerability was found; it included an analysis of medical facility locations in 14 Pacific Island countries, including in FSM, the Republic of the Marshall Islands, and Palau.[104]

There is significant evidence in the international Pacific Islands region that the current and future projected impacts of climate change are negatively affecting peoples' mental health, although studies are lacking specifically in Hawai'i and the USAPI. Evidence also indicates that impacts are more severe for Indigenous Peoples because their central identity is tied to an ancestral place. Studies linking climate impacts directly to mental health outcomes point to strong differences in how mental health impacts are experienced among different populations.[105,239,240,241,242] There is general agreement on the benefits of tailoring mental health services for Pacific Islanders to the specific needs of the population, including different services for migrants who have voluntarily or non-voluntarily migrated.[237,243]

There is strong evidence of the high prevalence and impact on human health of vector-borne disease in the Pacific Islands. Recent data from 2014 to 2020 document 104 dengue, chikungunya, and Zika outbreaks across Pacific Island countries and areas.[246] Literature agrees that the viruses had unexpected virulence and epidemic potential[245,247] and that future climate-driven spread and emergence of vector-borne diseases the Pacific region is expected.[247,249]

Multiple lines of evidence demonstrate the impacts of high and extreme temperatures on human health.[220,459] Substantial and growing evidence supports the disproportionate and acute effects of heat on vulnerable populations.[220] However, analysis of the burden of heat-related illness and death among specific populations in Hawai'i and the Pacific Islands is lacking.

Social and community adaptive capacity has a long history and broad disciplinary foundations, with many studies specific to Pacific Island countries and territories highlighting the importance of social capital, cultural norms, Traditional and Indigenous Knowledge, and women's voices in successful adaptation and disaster response (e.g., Bryant-Tokolau 2018;[260] Cinner and Barnes 2019;[460] Cohen et al. 2016;[461] McNamara et al. 2020;[321] Nunn et al. 2020;[462] Warrick et al. 2017[463]).

The literature on necessary adaptations for Pacific Island public health systems is relatively underdeveloped compared to the global literature on the topic. For example, a study of Organization for Economic Co-operation and Development countries' national-level public health adaptation found a diverse array of adaptations related to cross-sectoral collaboration, vertical coordination, and national health adaptation planning.[264] Two studies focus on needed adaptations in the Pacific Islands,[227,265] while the World Health Organization[267] produced national climate change and health vulnerability assessments to guide health system adaptation plans.

### Major Uncertainties and Research Gaps

Trends and changes in climate extremes in the USAPI represent a current research gap. Studies that account for compound or cascading extremes can best inform planning. Extreme event attribution studies

for Pacific Islands and Hawai'i would improve confidence and understanding of the role of climate change in driving societal impacts from extreme weather and climate events. The region lacks site-specific vulnerability assessments for critical health infrastructure. Dynamic inundation models that include wave-driven flooding and future scenario planning tools for coral reef–protected shorelines can improve understanding of health infrastructure vulnerability.

Few studies specifically investigate climate change impacts on mental health in Hawai'i and the USAPI, which, given the evidence that effective interventions must be culturally appropriate and tailored, indicates a strong need for additional research. Few studies in the region specifically address the mental health impacts of climate-induced migration on displaced populations. New research can point to ways to build personal resilience to climate change among frontline workers and climate adaptation practitioners, a topic preliminary research has examined.[464]

Changes in climate are expected to exacerbate the increasing risk of vector-borne disease transmission throughout the region, and various species of invasive mosquitoes are already linked to outbreaks of Zika, chikungunya, and dengue. The ways in which climate change will affect disease emergence are complex and yet to be fully explored. Place-based surveillance to assess the association between climate factors and infections, as well as climate early warning systems for vector-borne disease, would help better understand and prevent epidemics.

Regional stakeholders have called for community-based approaches to research assessing climate change readiness. Such research may include assessments of community strengths and local knowledge, community-led pilot initiatives, and identification of priorities for climate resilience planning.[27]

## Description of Confidence and Likelihood

There is *high confidence* that warming temperatures, impacts from tropical cyclones, food and freshwater insecurity, and flooding are already negatively impacting human health in the Pacific Islands region. This is based on agreement among multiple lines of evidence, including peer-reviewed publications and reports and national and regional government reports, that show increases in heat-related illness and vector-borne diseases, damage to critical infrastructure, and psychological stress. Documented impacts to critical electric, medical, and transit infrastructure provide evidence that healthcare services have been compromised, although formal assessments of regional healthcare infrastructure are lacking, resulting in an assignment of *medium confidence*. Data linking local climate impacts such as drought and flooding with negative direct and indirect health outcomes in different communities in the international Pacific Islands demonstrate that there is *high confidence* that these impacts have worsened existing health inequities in both physical and mental health across the region. Based on current scientific consensus, there is *very high confidence* that the drivers of the negative impacts of climate change, such as high temperatures and SLR, are expected to worsen in the future. Meta-studies show that examples of health and disaster adaptations and recovery that center Indigenous ways of knowing and social cohesion have had success in the region, and there is *high confidence* that expanding these activities will increase resilience.

## Key Message 30.3

# Rising Sea Levels Threaten Infrastructure and Local Economies and Exacerbate Existing Inequities

### Description of Evidence Base

The finding that climate change, especially SLR, will continue to negatively impact buildings, infrastructure, and the built environment is based on future projections of SLR (App. 3) encompassed in a suite of scenarios that include physical and socioeconomic factors from Sweet et al. (2022).[65] Available literature agrees that wave-driven flooding and high sea level events and associated inundation will continue to increase in frequency and severity.[98,218,219,465] There is scientific consensus that tropical cyclone (TC) intensity is increasing globally with warming.[70,216] One study of TC changes shows a likelihood of fewer but possibly stronger storms (increasing maximum intensities) in the northwestern Pacific.[53]

Mycoo et al. (2022)[89] have extensively documented the impacts of SLR, heavy rain events, TCs, and storm surges on the coastal built environment and rural communities on small islands. The primary sources of economic data for Freely Associated States are the Asian Development Bank, the World Bank (2022b);[22] United Nations, and the CIA World Factbook economic impact (costs) studies. Population figures and trends for American Sāmoa, the Commonwealth of the Northern Mariana Islands, Guam, and Hawai'i are from the US Census.[19,20,21]

### Major Uncertainties and Research Gaps

Wave run-up models incorporating Sweet et al. (2022)[65] SLR scenarios are not yet available. Needed for the development of wave run-up models are high resolution elevation and water depth data (topobathymetric information), which are currently lacking for many Pacific Islands.

The amount and timing of future SLR experienced across the region is a key area of remaining uncertainty. There is uncertainty in the physical processes—particularly marine ice sheet instability and marine ice cliff instability—that could lead to rapid ice mass loss over a period of several decades (KM 3.3).

There is uncertainty in the effectiveness of migration as a climate change adaptation strategy, as the outcomes are dependent on individual situations and there is limited evidence in the literature.[69,89,466,467,468,469,470,471] Anthropological and population geography literature (e.g., Connell and Brown 2005[293]) for Micronesia establishes that past and present migration was an adaptation strategy associated with resource scarcity and that, historically, migrants traveled for economic and educational reasons.[472] There is limited current empirical evidence of migration that includes historical records of disaster-driven displacement; projections of displacement are also not available.

There is a gap in the literature examining the linkages between climate change, transport, and tourism, as well as the impacts of ecological change and heat on tourism demand. Future economic losses and impacts to livelihoods due to climate change–driven invasive species distribution shifts are understudied. For example, recent coconut rhinoceros beetle (CRB) invasions in Guam and Hawai'i and impacts on coconut palms have led to economic losses and declines in aesthetic value and have threatened food security.[473] Increased invasion of CRB following strong tropical cyclones is apparent,[474,475] but the specific interactions between climate factors and invasions are not yet well studied. The invasive brown tree snake on Guam has caused billions of dollars in damage to infrastructure[476] and causes up to 200 electrical blackouts per year,[477] adding stress to Guam's electrical grid, which is already facing compound climate stressors; the economic costs of species invasions in a changing climate are likely underestimated.

More guidance is needed on how equity, inclusion, and justice can be embedded in decision-making across the diverse governance arrangements in the region.[478]

Research on nature-based solutions has improved considerably,[322,479,480] although there is limited research evaluating the benefits, economic efficiency, and long-term effectiveness of these solutions.[89,481,482] Recent literature has examined the effectiveness of protection services that mangroves provide, which has important implications for long-range adaptation planning on islands (e.g., Saintilan et al. 2020;[355] Sasmito et al. 2016;[483] Zeng et al. 2021[484]).

### Description of Confidence and Likelihood

It is *very likely* and there is *high confidence* that SLR will continue to damage the coastal built environment in the Pacific Islands region. This is documented by multiple lines of evidence, including peer-reviewed literature, planning documents, models, and government reports analyzing flooding, erosion, and wave impacts on coastal infrastructure across the region.

It is *very likely* and there is *high confidence* that climate impacts, including SLR, drought, and storms, will impact key economic sectors, such as tourism and fisheries. These likelihood and confidence assignments are based on peer-reviewed literature, strategic planning documents, development bank reports, and government reports detailing the projected impacts on and understanding of the behavioral, logistical, and biological features of these economic sectors.

There is *high confidence* of the potential for loss of territory and maritime entitlements, particularly in low islands, based on models, reports from governments, international financial institutions, and international meetings.

It is *likely* and there is *medium confidence* that climate-driven changes will exacerbate existing social challenges, thereby disrupting livelihoods. Evidence related to livelihoods disruptions under future scenarios remains sparse and will vary across contexts, thus the assignment of *medium confidence*. *High confidence* in the higher costs of adaptation and disaster recovery in islands is based on various factors that characterize islands, including geographic isolation (e.g., ASCE 2020[224]), reliance on imported materials and labor, vulnerable infrastructure, and sensitive ecosystems.

## Key Message 30.4

## Responses to Rising Threats May Help Safeguard Tropical Ecosystems and Biodiversity

### Description of Evidence Base

Based on consensus across the cited literature and the latest available climate projections, there is *high confidence* across all future scenarios that deteriorating climate conditions will continue to threaten regional ecosystems and biodiversity throughout the this century (e.g., Buffington et al. 2021;[86] Eakin et al. 2019;[61] Fortini et al. 2015;[93] Gove et al. 2022;[62] Jacobi and Warshauer 2017;[354] Kwiatkowski et al. 2020;[60] Liao et al. 2015;[94] Lotze et al. 2019;[331] Reynolds et al. 2015;[356] Palacios-Abrantes et al. 2022[83]).

Projections of how physical changes will affect ecosystems come from a range of approaches: ecosystem and food web modeling, statistical modeling, and extrapolations from change already observed. Despite the data inequities present across the region (Box 30.1), there are multiple observations documenting past and ongoing changes in marine and terrestrial ecosystems and their physical environments (e.g., Dendy et al. 2022;[229] Judge et al. 2021;[414] Raymundo et al. 2019[334]).

## Major Uncertainties and Research Gaps

The adaptive capacity of organisms and ecosystems in the face of climate change remains uncertain. For example, there is uncertainty about the plankton community's response to climate change, which will influence the effect of climate change on higher-trophic-level organisms such as those targeted by subsistence, commercial, and recreational fisheries. Ecosystem response to simultaneous stressors and novel climate conditions is a complex subject area with high uncertainty. The effects of climate change on fish stocks outside the EEZs are underexplored.

While regional climate projections and historical climate analyses for Hawai'i have been developed, similar sets of studies for USAPI are much more limited, lowering our confidence in projected terrestrial impacts of climate in other US-affiliated jurisdictions (e.g., future wildfire probabilities).[376] This gap in available climate data and projections is paralleled in the Caribbean region (KM 23.2), indicating a broad uncertainty for the future of our Nation's island areas.

The impacts of extreme events on Pacific Island terrestrial ecosystems are still poorly studied given the limited data to characterize past and current events and project future shifts in intensity and frequency of such events. These uncertainties in extreme event impacts on island ecosystems are similar to those identified in the Caribbean chapter (see Traceable Account, KM 23.2), highlighting a common challenge faced by underserved island areas.

The societal response to regional climate impacts can have a large impact on surrounding ecosystems and is also a major area of uncertainty.

## Description of Confidence and Likelihood

There is *high confidence* and it is *very likely* that the structure and composition of Pacific Island coastal and marine ecological communities are directly threatened by ocean changes. This assessment is based on similarities across climate scenarios through the mid-21st century, as well as on the degree to which climate conditions have already impacted regional ecosystems and biodiversity, and given species-specific climate and habitat tolerances.

Fire is already a substantial challenge to Pacific Islands (Figure 30.13),[229,378] with risks expected to rise under additional warming and drying (*high confidence*).[376] A wide body of literature links increasing droughts and temperatures to increased fire risk (Chs. 7, 8).

Regarding native plants, climatic shifts have already been shown to influence plant communities, from broad landscape shifts to individual species population trends (*very likely*, *high confidence*).[364,365,366,370] Future projections indicate continued and drastic effects.[93,367] Regarding forest birds and other wildlife, the link between forest bird declines in Hawai'i and warming is clear,[414,415] with underlying mechanisms well understood.[485,486] These declining trends are consistently projected to continue under additional warming (*very likely*, *high confidence*).[93,94]

There is *medium confidence* in the ability of certain adaptation strategies to improve the resilience of Pacific Island ecosystems. Ecological restoration efforts and invasive species prevention, eradication, and control enhance regional climate resilience and provide multiple benefits to islands (e.g., KM 8.3; Barbosa and Asner 2017;[398] Bremer et al. 2018;[202] Ferrario et al. 2014;[289] Wada et al. 2017[401]), including helping to reduce water stress and fire risk (e.g., KM 8.2; Dudley et al. 2020;[388] Fortini et al. 2021;[380] Strauch et al. 2017;[148] Trauernicht 2019[376]). However, due to the uncertainties in regional projections and climate and invasive species interactions, there is *medium confidence* in restoration and invasive species control efforts. The establishment and management of protected areas are also widely considered effective components of ecological adaptation strategies,[119] but large climatic shifts may reduce their effectiveness over time,[399] leading to *medium confidence* in their long-term effectiveness. Fire management strategies have been shown to be quite

effective across the Pacific Islands region.[125] However, the effectiveness of these strategies under extreme fire conditions is expected to be reduced (e.g., atypically high wind and dry conditions), thus *medium confidence*.

## Key Message 30.5

## Indigenous Knowledge Systems Strengthen Island Resilience

### Description of Evidence Base

There is no doubt that fostering reciprocal relationships between people, place, and cultural and historical sites across Hawai'i and the USAPI is central to the ongoing adaptation of island communities to the changing climate (e.g., Diver et al. 2019;[430] Nunn et al. 2017[87]). However, these types of relationships are usually documented in an oral rather than written format. For the most part, there is agreement that the culture of Indigenous Peoples influences their interpretation of the value of place and ecosystems and, subsequently, their resilience to climate change. The studies cited in this section use the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report CMIP5 results for temperature, rainfall, and SLR to assess impacts on traditional foods and cultural resources.[118,434,442]

### Major Uncertainties and Research Gaps

Research that assesses the impacts of climate change (SLR, temperature, etc.) on cultural resources and historical sites is limited and largely focused on Hawai'i. Many of the studies that assess climate-related impacts to cultural resources were published prior to the release of the updated IPCC Sixth Assessment Report and NOAA's updated SLR projections. There is limited information on how climate change–driven shifts in the distributions of invasive plants and animals may disrupt cultural services and familial relationships (e.g., Brewington et al. 2023[359]).

### Description of Confidence and Likelihood

Literature focused on community and place-based approaches to natural resource management supports that there is *high confidence* that Indigenous Peoples of the Pacific Islands, their knowledge systems, and their rituals are central to local climate resilience. Literature also supports that there is *high confidence* that reciprocal and spiritual relationships among people and place are being strengthened through adaptation and collective management of resources.

There is *high confidence* that the application of future climate scenarios has enabled the collective efforts of Indigenous researchers, stakeholders, and scientists to begin to identify and quantify the potential loss and migration of critical resources and expand the cultivation of traditional food crops on high islands. However, such assessments are limited in scope across Hawai'i and the USAPI, and as a result the impacts of climate change on cultural resources are still identified as a major gap in knowledge.

# References


1. Finney, B., 1997: Pacific Islanders at sea. *American Anthropologist*, **99** (2), 403–404. https://doi.org/10.1525/aa.1997.99.2.403

2. Clarke, W.C. and R.R. Thaman, Eds., 1993: *Agroforestry in the Pacific Islands: Systems for Sustainability*. United Nations University Press, 307 pp. https://archive.unu.edu/unupress/unupbooks/80824e/80824e00.htm

3. Falanruw, M.V.C., 1993: Micronesian agroforestry: Evidence from the past, implications for the future. In: *Proceedings of the Workshop on Research Methodologies and Applications for Pacific Island Agroforestry; July 16–20, 1990; Kolonia, Pohnpei, Federated States of Micronesia*. Raynor, B. and R.R. Bay, Eds. Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, Albany, CA, 37–41. https://www.srs.fs.usda.gov/pubs/27382

4. Manner, H.I., 1993: A review of traditional agroforestry in Micronesia. In: *Proceedings of the Workshop on Research Methodologies and Applications for Pacific Island Agroforestry; July 16–20, 1990; Kolonia, Pohnpei, Federated States of Micronesia*. Raynor, B. and R.R. Bay, Eds. Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, Albany, CA, 32–36. https://www.fs.usda.gov/research/treesearch/27381

5. Raynor, B. and J. Fownes, 1993: An Indigenous Pacific Island agroforestry system: Pohnpei Island. In: *Proceedings of the Workshop on Research Methodologies and Applications for Pacific Island Agroforestry; July 16–20, 1990; Kolonia, Pohnpei, Federated States of Micronesia*. Raynor, B. and R.R. Bay, Eds. Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, Albany, CA, 42–58. https://www.fs.usda.gov/research/treesearch/27383

6. Falanruw, M.V.C., 1994: Traditional fishing in Yap. In: *Science of Pacific Peoples: Ocean and Coastal Shores*. Bluebird Printery, Suva, Fiji, 41–58. [Print].

7. Johannes, R.E., 1978: Traditional marine conservation methods in Oceania and their demise. *Annual Review of Ecology and Systematics*, **9** (1), 349–364. https://doi.org/10.1146/annurev.es.09.110178.002025

8. Johannes, R.E., 1981: *Words of the Lagoon: Fishing and Marine Lore in the Palau District of Micronesia*. University of California Press, Berkeley, CA. https://georgehbalazs.com/wp-content/uploads/2019/05/1981-WORDS-OF-THE-LAGOON-FISHING-MARINE-LORE-IN-THE-PALAU-DISTRICT-OF-MICRONESIA-EPILOGUE-PREFACE-ACKNOWLEGEMENTS-INDEXED-PAGES-FOR-TURTLES-1.pdf

9. Taafaki, I.J., M.K. Fowler, and R.R. Thaman, 2006: *Traditional Medicine of the Marshall Islands: The Women, the Plants, the Treatments*. University of the South Pacific, Institute of Pacific Studies, 300 pp. https://books.google.com/books/about/Traditional_Medicine_of_the_Marshall_Isl.html?id=xBxbCLXGwQkC

10. Elliott, M., M.C. MacDonald, T. Chan, A. Kearton, K.F. Shields, J.K. Bartram, and W.L. Hadwen, 2017: Multiple household water sources and their use in remote communities with evidence from Pacific island countries. *Water Resources Research*, **53** (11), 9106–9117. https://doi.org/10.1002/2017wr021047

11. Poyer, L., 1991: Ch. 7. Micronesian experiences of the War in the Pacific. In: *Remembering the Pacific War*. White, G.M., Ed. Center for Pacific Islands Studies, School of Hawaiian, Asian, and Pacific Studies, University of Hawai'i at Mānoa, Honolulu, HI, 79–89. http://hdl.handle.net/10125/15555

12. Cocklin, C., 1999: Ch. 9. Islands in the midst: Environmental change, vulnerability, and security in the Pacific. In: *Environmental Change, Adaptation, and Security*. Lonergan, S.C., Ed. Springer, Dordrecht, Netherlands, 141–159. https://doi.org/10.1007/978-94-011-4219-9_9

13. Simon, S.L., 1997: A brief history of people and events related to atomic weapons testing in the Marshall Islands. *Health Physics*, **73** (1). https://doi.org/10.1097/00004032-199707000-00001

14. Spencer, M.S., T. Fentress, A. Touch, and J. Hernandez, 2020: Environmental justice, Indigenous knowledge systems, and Native Hawaiians and other Pacific Islanders. *Human Biology*, **92** (1), 45–57. https://doi.org/10.13110/humanbiology.92.1.06

15. Keener, V., J.J. Marra, M.L. Finucane, D. Spooner, and M.H. Smith, Eds., 2012: *Climate Change and Pacific Islands: Indicators and Impacts. Report for The 2012 Pacific Islands Regional Climate Assessment*. Island Press, Washington, DC. https://www.reefresilience.org/pdf/NCA-PIRCA-FINAL.pdf

16. U.S. Census Bureau. 2013: 2010 Island Areas - American Samoa Dataset. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/datasets/2010/dec/american-samoa.html

17. U.S. Census Bureau. 2013: 2010 Island Areas - Commonwealth of the Northern Mariana Islands Dataset. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/datasets/2010/dec/cnmi.html

18. U.S. Census Bureau. 2013: 2010 Island Areas - Guam Dataset. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/datasets/2010/dec/guam.html

19. U.S. Census Bureau, 2022: 2020 Island Areas Censuses: Guam. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/tables/2020/dec/2020-guam.html

20. U.S. Census Bureau, 2022: 2020 Island Areas Censuses: American Samoa. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/tables/2020/dec/2020-american-samoa.html

21. U.S. Census Bureau, 2022: 2020 Island Areas Censuses: Commonwealth of the Northern Mariana Islands (CNMI). U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/data/tables/2020/dec/2020-commonwealth-northern-mariana-islands.html

22. The World Bank. 2022: Agriculture, forestry, and fishing, value added (% of GDP) - American Samoa, Palau, Micronesia, Fed. Sts., Guam, Marshall Islands. World Bank Group. https://data.worldbank.org/indicator/nv.agr.totl.zs?locations=as-pw-fm-gu-mh

23. U.S. Census Bureau, 2022: Quick Facts: Hawaii. U.S. Department of Commerce, U.S. Census Bureau. https://www.census.gov/quickfacts/fact/table/HI

24. Semega, J. and M. Kollar, 2022: Income in the United States: 2021. P60-276. U.S. Department of Commerce, U.S. Census Bureau, Washington, DC. https://www.census.gov/library/publications/2022/demo/p60-276.html

25. Techera, E.J., 2013: Ch. 16. Climate change, legal governance and the Pacific Islands: An overview. In: *Climate Change and Indigenous Peoples*. Abate, R.S. and E.A. Kronk, Eds. Edward Elgar Publishing, Cheltenham, UK, 339–362. https://doi.org/10.4337/9781781001806.00030

26. Keener, V., D. Helweg, S. Asam, S. Balwani, M. Burkett, C. Fletcher, T. Giambelluca, Z. Grecni, M. Nobrega-Olivera, J. Polovina, and G. Tribble, 2018: Ch. 27. Hawai'i and U.S.-affiliated Pacific Islands. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1242–1308. https://doi.org/10.7930/nca4.2018.ch27

27. Grecni, Z., E.M. Derrington, R. Greene, W. Miles, and V. Keener, 2021: Climate Change in the Commonwealth of the Northern Mariana Islands: Indicators and Considerations for Key Sectors. East-West Center, Honolulu, HI. https://doi.org/10.5281/zenodo.4426942

28. Grecni, Z., W. Miles, R. King, A. Frazier, and V. Keener, 2020: Climate Change in Guam: Indicators and Considerations for Key Sectors. East-West Center, Honolulu, HI. https://doi.org/10.5281/zenodo.4037481

29. Keener, V., Z. Grecni, K. Anderson Tagarino, C. Shuler, and W. Miles, 2021: Climate Change in American Sāmoa: Indicators and Considerations for Key Sectors. East-West Center, Honolulu, HI. https://doi.org/10.5281/zenodo.4663397

30. Polhemus, D.A., 2017: Drought in the U.S.-Affiliated Pacific Islands: A Multi-level Assessment. U.S. Fish and Wildlife Service, Pacific Islands Fish and Wildlife Office. https://doi.org/10.21429/c9zs74

31. Barnett, J., 2020: Ch. 2. Climate change and food security in the Pacific Islands. In: *Food Security in Small Island States*. Connell, J. and K. Lowitt, Eds. Springer, Singapore, 25–38. https://doi.org/10.1007/978-981-13-8256-7_2

32. Dyer, J., 2018: Ch. 20. Predicting true climate change risks and opportunities in the Cook Islands: How vulnerable are Pacific maritime supply chain stakeholders? In: *Climate Change Impacts and Adaptation Strategies for Coastal Communities*. Leal Filho, W., Ed. Springer, Cham, Switzerland, 373–408. https://doi.org/10.1007/978-3-319-70703-7_20

33. Johnson, J.E., V. Allain, B. Basel, J.D. Bell, A. Chin, L.X.C. Dutra, E. Hooper, D. Loubser, J. Lough, B.R. Moore, and S. Nicol, 2020: Ch. 10. Impacts of climate change on marine resources in the Pacific Island Region. In: *Climate Change and Impacts in the Pacific*. Kumar, L., Ed. Springer, Cham, Switzerland, 359–402. https://doi.org/10.1007/978-3-030-32878-8_10

34. McIver, L., M. Hashizume, H. Kim, Y. Honda, M. Pretrick, S. Iddings, and B. Pavlin, 2015: Assessment of climate-sensitive infectious diseases in the Federated States of Micronesia. *Tropical Medicine and Health*, **43** (1), 29–40. https://doi.org/10.2149/tmh.2014-17

35. Keener, V.W., Z.N. Grecni, and S.C. Moser, 2022: Accelerating climate change adaptive capacity through regional sustained assessment and evaluation in Hawai'i and the U.S. affiliated Pacific Islands. *Frontiers in Climate*, **4**, 869760. https://doi.org/10.3389/fclim.2022.869760

36. OSTP, 2022: Guidance for Federal Departments and Agencies on Indigenous Knowledge. White House Office of Science and Technology Policy, Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2022/12/ostp-ceq-ik-guidance.pdf

37. Winter, K.B., M.B. Vaughan, N. Kurashima, L. Wann, E. Cadiz, A.H. Kawelo, M. Cypher, L. Kaluhiwa, and H.K. Springer, 2023: Indigenous stewardship through novel approaches to collaborative management in Hawai'i. *Ecology and Society*, **28** (1). https://doi.org/10.5751/es-13662-280126

38. Keener, V., D. Helweg, S. Asam, S. Balwani, M. Burkett, C. Fletcher, T. Giambelluca, Z. Grecni, M. Nobrega-Olivera, J. Polovina, and G. Tribble, 2018: Box 27.1 in Ch. 27. Hawai'i and U.S.-affiliated Pacific Islands. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1242–1308. https://doi.org/10.7930/nca4.2018.ch27

39. Frazier, A.G., O. Elison Timm, T.W. Giambelluca, and H.F. Diaz, 2018: The influence of ENSO, PDO and PNA on secular rainfall variations in Hawai'i. *Climate Dynamics*, **51** (5), 2127–2140. https://doi.org/10.1007/s00382-017-4003-4

40. Mantua, N.J. and S.R. Hare, 2002: The Pacific decadal oscillation. *Journal of Oceanography*, **58** (1), 35–44. https://doi.org/10.1023/a:1015820616384

41. PEAC Center, 2016: PEAC Seasonal Sea Level Outlook: Current Conditions. National Weather Service, Pacific ENSO Applications Climate Center. http://www.weather.gov/peac/sealevel

42. Hamlington, B.D., T. Frederikse, P.R. Thompson, J.K. Willis, R.S. Nerem, and J.T. Fasullo, 2021: Past, present, and future Pacific sea-level change. *Earth's Future*, **9** (4), e2020EF001839. https://doi.org/10.1029/2020ef001839

43. Sweet, W., S. Simon, G. Dusek, D. Marcy, W. Brooks, M. Pendleton, and J. Marra, 2021: 2021 State of High Tide Flooding and Annual Outlook. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD. https://tidesandcurrents.noaa.gov/publications/2021_State_of_High_Tide_Flooding_and_Annual_Outlook_Final.pdf

44. Thompson, P.R., M.J. Widlansky, M.A. Merrifield, J.M. Becker, and J.J. Marra, 2019: A statistical model for frequency of coastal flooding in Honolulu, Hawaii, during the 21st century. *Journal of Geophysical Research: Oceans*, **124** (4), 2787–2802. https://doi.org/10.1029/2018jc014741

45. Marra, J.J., G. Gooley, M.-V. Johnson, V. Keener, M. Kruk, S. McGree, J.T. Potemra, and O. Warrick, 2022: Pacific Islands Climate Change Monitor: 2021. The Pacific Islands-Regional Climate Centre Network Report to the Pacific Islands Climate Service Panel and Pacific Meteorological Council. https://doi.org/10.5281/zenodo.6965143

46. McKenzie, M.M., T.W. Giambelluca, and H.F. Diaz, 2019: Temperature trends in Hawai'i: A century of change, 1917–2016. *International Journal of Climatology*, **39** (10), 3987–4001. https://doi.org/10.1002/joc.6053

47. Elison Timm, O., 2017: Future warming rates over the Hawaiian Islands based on elevation-dependent scaling factors. *International Journal of Climatology*, **37**, 1093–1104. https://doi.org/10.1002/joc.5065

48. Frazier, A.G. and T.W. Giambelluca, 2017: Spatial trend analysis of Hawaiian rainfall from 1920 to 2012. *International Journal of Climatology*, **37** (5), 2522–2531. https://doi.org/10.1002/joc.4862

49. Frazier, A.G., C.P. Giardina, T.W. Giambelluca, L. Brewington, Y.-L. Chen, P.-S. Chu, L. Berio Fortini, D. Hall, D.A. Helweg, V.W. Keener, R.J. Longman, M.P. Lucas, A. Mair, D.S. Oki, J.J. Reyes, S.G. Yelenik, and C. Trauernicht, 2022: A century of drought in Hawai'i: Geospatial analysis and synthesis across hydrological, ecological, and socioeconomic scales. *Sustainability*, **14** (19), 12023. https://doi.org/10.3390/su141912023

50. McGree, S., S. Schreider, and Y. Kuleshov, 2016: Trends and variability in droughts in the Pacific islands and Northeast Australia. *Journal of Climate*, **29** (23), 8377–8397. https://doi.org/10.1175/jcli-d-16-0332.1

51. Elison Timm, O., T.W. Giambelluca, and H.F. Diaz, 2015: Statistical downscaling of rainfall changes in Hawai'i based on the CMIP5 global model projections. *Journal of Geophysical Research: Atmospheres*, **120** (1), 92–112. https://doi.org/10.1002/2014jd022059

52. Shuler, C., L. Brewington, and A.I. El-Kadi, 2021: A participatory approach to assessing groundwater recharge under future climate and land-cover scenarios, Tutuila, American Samoa. *Journal of Hydrology: Regional Studies*, **34**, 100785. https://doi.org/10.1016/j.ejrh.2021.100785

53. Widlansky, M.J., H. Annamalai, S.B. Gingerich, C.D. Storlazzi, J.J. Marra, K.I. Hodges, B. Choy, and A. Kitoh, 2019: Tropical cyclone projections: Changing climate threats for Pacific island defense installations. *Weather, Climate, and Society*, **11** (1), 3–15. https://doi.org/10.1175/wcas-d-17-0112.1

54. Bloemendaal, N., H. de Moel, A.B. Martinez, S. Muis, I.D. Haigh, K. van der Wiel, R.J. Haarsma, P.J. Ward, M.J. Roberts, J.C.M. Dullaart, and J.C.J.H. Aerts, 2022: A globally consistent local-scale assessment of future tropical cyclone risk. *Science Advances*, **8** (17), 8438. https://doi.org/10.1126/sciadv.abm8438

55. Knutson, T., S.J. Camargo, J.C.L. Chan, K. Emanuel, C.H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2020: Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, **101** (3), 303–322. https://doi.org/10.1175/bams-d-18-0194.1

56. Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A.D. Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, 2021: Ch. 11. Weather and climate extreme events in a changing climate. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1513–1766. https://doi.org/10.1017/9781009157896.013

57. Zhang, C., Y. Wang, K. Hamilton, and A. Lauer, 2016: Dynamical downscaling of the climate for the Hawaiian Islands. Part II: Projection for the late twenty-first century. *Journal of Climate*, **29** (23), 8333–8354. https://doi.org/10.1175/jcli-d-16-0038.1

58. Marra, J.J. and M.C. Kruk, 2017: State of Environmental Conditions in Hawaii and the U.S. Affiliated Pacific Islands Under a Changing Climate: 2017. National Oceanic and Atmospheric Administration, National Centers for Environmental Information. https://pirca.org/2017/11/30/state-of-environmental-conditions-in-hawaii-and-the-u-s-affiliated-pacific-islands-under-a-changing-climate-2017/

59. WPRFMC, 2021: Annual Stock Assessment and Fishery Evaluation Report Pacific Island Pelagic Fishery Ecosystem Plan 2020. Remington, T., M. Fitchett, A. Ishizaki, and J. DeMello, Eds. Western Pacific Regional Fishery Management Council, Honolulu, HI, 410 pp. https://www.wpcouncil.org/wp-content/uploads/2021/08/Pelagic-FEP-SAFE-Report-2020_v2.pdf

60. Kwiatkowski, L., O. Torres, L. Bopp, O. Aumont, M. Chamberlain, J.R. Christian, J.P. Dunne, M. Gehlen, T. Ilyina, J.G. John, A. Lenton, H. Li, N.S. Lovenduski, J.C. Orr, J. Palmieri, Y. Santana-Falcón, J. Schwinger, R. Séférian, C.A. Stock, A. Tagliabue, Y. Takano, J. Tjiputra, K. Toyama, H. Tsujino, M. Watanabe, A. Yamamoto, A. Yool, and T. Ziehn, 2020: Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. *Biogeosciences*, **17** (13), 3439–3470. https://doi.org/10.5194/bg-17-3439-2020

61. Eakin, C.M., H.P.A. Sweatman, and R.E. Brainard, 2019: The 2014–2017 global-scale coral bleaching event: Insights and impacts. *Coral Reefs*, **38** (4), 539–545. https://doi.org/10.1007/s00338-019-01844-2

62. Gove, J.M., J.A. Maynard, J. Lecky, D.P. Tracey, M.E. Allen, G.P. Asner, C. Conklin, C. Couch, K. Hum, R.J. Ingram, T.L. Kindinger, K. Leong, K.L.L. Oleson, E.K. Towle, R. van Hooidonk, G.J. Williams, and J. Hospital, 2022: 2022 Ecosystem Status Report for Hawai'i. PIFSC Special Publication, SP-23-01. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Pacific Islands Fisheries Science Center, 91 pp. https://doi.org/10.25923/r53p-fn97

63. Woodworth, P.L., A. Melet, M. Marcos, R.D. Ray, G. Wöppelmann, Y.N. Sasaki, M. Cirano, A. Hibbert, J.M. Huthnance, S. Monserrat, and M.A. Merrifield, 2019: Forcing factors affecting sea level changes at the coast. *Surveys in Geophysics*, **40** (6), 1351–1397. https://doi.org/10.1007/s10712-019-09531-1

64. Merrifield, M.A. and M.E. Maltrud, 2011: Regional sea level trends due to a Pacific trade wind intensification. *Geophysical Research Letters*, **38** (21). https://doi.org/10.1029/2011gl049576

65. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

66. Dhage, L. and M.J. Widlansky, 2022: Assessment of 21st century changing sea surface temperature, rainfall, and sea surface height patterns in the tropical Pacific islands using CMIP6 greenhouse warming projections. *Earth's Future*, **10** (4), e2021EF002524. https://doi.org/10.1029/2021ef002524

67. Arslanalp, S., R. Koepke, and J. Verschuur, 2021: Tracking trade from space: An application to Pacific Island countries. *IMF Working Papers*, **2021** (225), 40. https://doi.org/10.5089/9781513593531.001

68. Finkbeiner, E.M., F. Micheli, N.J. Bennett, A.L. Ayers, E. Le Cornu, and A.N. Doerr, 2018: Exploring trade-offs in climate change response in the context of Pacific Island fisheries. *Marine Policy*, **88**, 359–364. https://doi.org/10.1016/j.marpol.2017.09.032

69. Weir, T., L. Dovey, and D. Orcherton, 2017: Social and cultural issues raised by climate change in Pacific Island countries: An overview. *Regional Environmental Change*, **17** (4), 1017–1028. https://doi.org/10.1007/s10113-016-1012-5

70. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

71. Shuler, C.K., H. Dulai, R. DeWees, M. Kirs, C.R. Glenn, and A.I. El-Kadi, 2019: Isotopes, microbes, and turbidity: A multi-tracer approach to understanding recharge dynamics and groundwater contamination in a basaltic island aquifer. *Groundwater Monitoring & Remediation*, **39** (1), 20–35. https://doi.org/10.1111/gwmr.12299

72. Ichiho, H.M., F.T. Roby, E.S. Ponausuia, and N. Aitaoto, 2013: An assessment of non-communicable diseases, diabetes, and related risk factors in the territory of American Samoa: A systems perspective. *Hawai'i Journal of Medicine and Public Health*, **72** (5), 10. https://www.ncbi.nlm.nih.gov/pmc/articles/pmc3689461/

73. Bell, J.D., C. Reid, M.J. Batty, P. Lehodey, L. Rodwell, A.J. Hobday, J.E. Johnson, and A. Demmke, 2013: Effects of climate change on oceanic fisheries in the tropical Pacific: Implications for economic development and food security. *Climatic Change*, **119** (1), 199–212. https://doi.org/10.1007/s10584-012-0606-2

74. Feagaimaali'i, J., 2022: American Samoa experiencing massive coastal flooding. *Samoa News*, July 15, 2022. https://samoanews.com/local-news/american-samoa-experiencing-massive-coastal-flooding

75. Wyte-Lake, T., S. Schmitz, R.J. Kornegay, F. Acevedo, and A. Dobalian, 2021: Three case studies of community behavioral health support from the US Department of Veterans Affairs after disasters. *BMC Public Health*, **21** (1), 639. https://doi.org/10.1186/s12889-021-10650-x

76. Liske-Clark, J., 2015: Wildlife Action Plan for the Commonwealth of the Northern Mariana Islands: 2015–2025. CNMI Department of Land and Natural Resources, Division of Fish and Wildlife, Saipan, MP. https://opd.gov.mp/library/reports/cnmi-swap-2015-final.pdf

77. Taylor, M., A. McGregor, and B. Dawson, 2016: Vulnerability of Pacific Island Agriculture and Forestry to Climate Change. Pacific Community, Noumea, New Caledonia. https://www.fao.org/family-farming/detail/en/c/432913/

78. Bell, J., M. Batty, A. Ganachaud, P. Gehrke, A. Hobday, O. Hoegh-Guldberg, J. Johnson, R. Le Borgne, P. Lehodey, J. Lough, T. Pickering, M. Pratchett, M. Sheaves, and M. Waycott, 2009: Preliminary Assessment of the Effects of Climate Change on Fisheries and Aquaculture in the Pacific. Secretariat of the Pacific Community, 15 pp. https://library.sprep.org/sites/default/files/433.pdf

79. Bell, J.D., A. Cisneros-Montemayor, Q. Hanich, J.E. Johnson, P. Lehodey, B.R. Moore, M.S. Pratchett, G. Reygondeau, I. Senina, J. Virdin, and C.C.C. Wabnitz, 2018: Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. *Marine Policy*, **88**, 303–314. https://doi.org/10.1016/j.marpol.2017.05.019

80. Bell, J.D., C. Reid, M.J. Batty, E.H. Allison, P. Lehodey, L. Rodwell, T.D. Pickering, R. Gillett, J.E. Johnson, A. Hobday, and A. Demmke, 2011: Ch. 12. Implications of climate change for contributions by fisheries and aquaculture to Pacific Island economies and communities. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Bell, J.D., J.E. Johnson, and A.J. Hobday, Eds. Secretariat of the Pacific Community, 733–801. https://hdl.handle.net/20.500.12348/1067

81. Bell, J.D., I. Senina, T. Adams, O. Aumont, B. Calmettes, S. Clark, M. Dessert, M. Gehlen, T. Gorgues, J. Hampton, Q. Hanich, H. Harden-Davies, S.R. Hare, G. Holmes, P. Lehodey, M. Lengaigne, W. Mansfield, C. Menkes, S. Nicol, and P. Williams, 2021: Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, **4** (10), 900–910. https://doi.org/10.1038/s41893-021-00745-z

82. Farmery, A.K., J.M. Scott, T.D. Brewer, H. Eriksson, D.J. Steenbergen, J. Albert, J. Raubani, J. Tutuo, M.K. Sharp, and N.L. Andrew, 2020: Aquatic foods and nutrition in the Pacific. *Nutrients*, **12** (12), 3705. https://doi.org/10.3390/nu12123705

83. Palacios-Abrantes, J., T.L. Frölicher, G. Reygondeau, U.R. Sumaila, A. Tagliabue, Colette C.C. Wabnitz, and William W.L. Cheung, 2022: Timing and magnitude of climate-driven range shifts in transboundary fish stocks challenge their management. *Global Change Biology*, **28** (7), 2312–2326. https://doi.org/10.1111/gcb.16058

84. Andrew, N.L., P. Bright, L. de la Rua, S.J. Teoh, and M. Vickers, 2019: Coastal proximity of populations in 22 Pacific Island countries and territories. *PLoS ONE*, **14** (9), e0223249. https://doi.org/10.1371/journal.pone.0223249

85. Kumar, L. and S. Taylor, 2015: Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change*, **5** (11), 992–996. https://doi.org/10.1038/nclimate2702

86. Buffington, K.J., R.A. MacKenzie, J.A. Carr, M. Apwong, K.W. Krauss, and K.M. Thorne, 2021: Mangrove Species' Response to Sea-Level Rise across Pohnpei, Federated States of Micronesia. USGS Open-File Report 2021-1002. U.S. Geological Survey, 44 pp. https://doi.org/10.3133/ofr20211002

87. Nunn, P.D., J. Runman, M. Falanruw, and R. Kumar, 2017: Culturally grounded responses to coastal change on islands in the Federated States of Micronesia, northwest Pacific Ocean. *Regional Environmental Change*, **17** (4), 959–971. https://doi.org/10.1007/s10113-016-0950-2

88. Gingerich, S.B., A.G. Johnson, S.N. Rosa, M.D. Marineau, S.A. Wright, L.E. Hay, M.J. Widlansky, J.W. Jenson, C.I. Wong, J.L. Banner, V.W. Keener, and M.L. Finucane, 2019: Water Resources on Guam—Potential Impacts of and Adaptive Response to Climate Change. USGS Investigations Report 2019–5095. U.S. Geological Survey, 55 pp. https://doi.org/10.3133/sir20195095

89. Mycoo, M., M. Wairiu, D. Campbell, V. Duvat, Y. Golbuu, S. Maharaj, J. Nalau, P. Nunn, J. Pinnegar, and O.Warrick, 2022: Ch. 15. Small islands. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2043–2121. https://doi.org/10.1017/9781009325844.017

90. King, R., K. Bautista, M. Higgs, and E. Leon-Guerrero, 2019: Vulnerability Assessment of Built Infrastructure near Coastal Bays Using Three Sea Level Rise Scenarios – Guam. Government of Guam. https://bsp.guam.gov/guamccva/

91. Gordon, S., 2014: Heat illness in Hawai'i. *Hawai'i Journal of Medicine & Public Health*, **73** (11), 33–36. https://www.ncbi.nlm.nih.gov/pmc/articles/pmc4244899/

92. Hawai'i Climate Change Mitigation and Adaptation Commission, 2017: Hawai'i Sea Level Rise Vulnerability and Adaptation Report. Tetra Tech, Inc. and the State of Hawai'i Department of Land and Natural Resources, Office of Conservation and Coastal Lands. https://climateadaptation.hawaii.gov/wp-content/uploads/2017/12/SLR-Report_Dec2017.pdf

93. Fortini, L.B., A.E. Vorsino, F.A. Amidon, E.H. Paxton, and J.D. Jacobi, 2015: Large-scale range collapse of Hawaiian forest birds under climate change and the need 21st century conservation options. *PLoS ONE*, **10**, e0144311. https://doi.org/10.1371/journal.pone.0140389

94. Liao, W., O. Elison Timm, C. Zhang, C.T. Atkinson, D.A. LaPointe, and M.D. Samuel, 2015: Will a warmer and wetter future cause extinction of native Hawaiian forest birds? *Global Change Biology*, **21** (12), 4342–4352. https://doi.org/10.1111/gcb.13005

95. Kauahi, C. 2018: Hydrology of Three Loko I'a, Hawaiian Fishponds, on Windward Hawai'i Island, Hawai'i. Master of Science in Tropical Conservation Biology and Environmental Science, University of Hawai'i at Hilo, 60 pp. http://hdl.handle.net/10790/3536

96. Marrack, L. and P. O'Grady, 2014: Predicting Impacts of Sea Level Rise for Cultural and Natural Resources in Five National Park Units on the Island of Hawai'i. Technical report, 188. University of Hawaii at Manoa, Pacific Cooperative Studies Unit, Honolulu, HI, 40 pp. http://hdl.handle.net/10125/34111

97. Sproat, D.K., 2016: An Indigenous people's right to environmental self-determination: Native Hawaiians and the struggle against climate change devastation. *Stanford Environmental Law Journal*, **35** (2). https://law.stanford.edu/publications/an-indigenous-peoples-right-to-environmental-self-determination-native-hawaiians-and-the-struggle-against-climate-change-devastation/

98. Storlazzi, C.D., S.B. Gingerich, A. van Dongeren, O.M. Cheriton, P.W. Swarzenski, E. Quataert, C.I. Voss, D.W. Field, H. Annamalai, G.A. Piniak, and R. McCall, 2018: Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, **4** (4), 9741. https://doi.org/10.1126/sciadv.aap9741

99. Albrecht, G., G.-M. Sartore, L. Connor, N. Higginbotham, S. Freeman, B. Kelly, H. Stain, A. Tonna, and G. Pollard, 2007: Solastalgia: The distress caused by environmental change. *Australasian Psychiatry*, **15** (Sup1), S95–S98. https://doi.org/10.1080/10398560701701288

100. Fox, M.D., A.L. Carter, C.B. Edwards, Y. Takeshita, M.D. Johnson, V. Petrovic, C.G. Amir, E. Sala, S.A. Sandin, and J.E. Smith, 2019: Limited coral mortality following acute thermal stress and widespread bleaching on Palmyra Atoll, central Pacific. *Coral Reefs*, **38** (4), 701–712. https://doi.org/10.1007/s00338-019-01796-7

101. Baker, J.D., C.L. Littnan, and D.W. Johnston, 2006: Potential effects of sea level rise on the terrestrial habitats of endangered and endemic megafauna in the Northwestern Hawaiian Islands. *Endangered Species Research*, **2**, 21–30. https://doi.org/10.3354/esr002021

102. Kikiloi, K. and M. Graves, 2010: Ch. 4. Rebirth of an archipelago: Sustaining a Hawaiian cultural identity for people and homeland. In: *Hulili: Multidisplinary Research on Hawaiian Well-Being*. University of Hawai'i Press, 73–116. https://ulukau.org/ulukau-books/?a=d&d=EBOOK-HULILI2010&l=haw

103. Frazier, A.G., J.L. Deenik, N.D. Fujii, G.R. Funderburk, T.W. Giambelluca, C.P. Giardina, D.A. Helweg, V.W. Keener, A. Mair, J.J. Marra, S. McDaniel, L.N. Ohye, D.S. Oki, E.W. Parsons, A.M. Strauch, and C. Trauernicht, 2019: Ch. 5. Managing effects of drought in Hawai'i and U.S.-affiliated Pacific Islands. In: *Effects of Drought on Forests and Rangelands in the United States: Translating Science Into Management Responses*. Vose, J.M., D.L. Peterson, C.H. Luce, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 95–121. https://www.fs.usda.gov/research/treesearch/59164

104. Taylor, S., 2021: The vulnerability of health infrastructure to the impacts of climate change and sea level rise in small island countries in the South Pacific. *Health Services Insights*, **14**, 11786329211020857. https://doi.org/10.1177/11786329211020857

105. Krzesni, D. and L. Brewington, 2022: Climate Change, Health, and Migration: Profiles of Resilience and Vulnerability in the Marshall Islands. East-West Center, Honolulu, HI, 70 pp. https://www.eastwestcenter.org/publications/climate-change-health-and-migration-profiles-resilience-and-vulnerability-in-the

106. Masselink, G., R. McCall, E. Beetham, P. Kench, and C. Storlazzi, 2021: Role of future reef growth on morphological response of coral reef islands to sea-level rise. *Journal of Geophysical Research: Earth Surface*, **126** (2), e2020JF005749. https://doi.org/10.1029/2020jf005749

107. McLean, R. and P. Kench, 2015: Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? *WIREs Climate Change*, **6** (5), 445–463. https://doi.org/10.1002/wcc.350

108. Storlazzi, C.D., E.P.L. Elias, and P. Berkowitz, 2015: Many atolls may be uninhabitable within decades due to climate change. *Scientific Reports*, **5**, 14546. https://doi.org/10.1038/srep14546

109. Lam, V.W.Y., E.H. Allison, J.D. Bell, J. Blythe, W.W.L. Cheung, T.L. Frölicher, M.A. Gasalla, and U.R. Sumaila, 2020: Climate change, tropical fisheries and prospects for sustainable development. *Nature Reviews Earth & Environment*, **1** (9), 440–454. https://doi.org/10.1038/s43017-020-0071-9

110. Rudiak-Gould, P., 2014: The influence of science communication on Indigenous climate change perception: Theoretical and practical implications. *Human Ecology*, **42** (1), 75–86. https://doi.org/10.1007/s10745-013-9605-9

111. McLeod, E., S. Arora-Jonsson, Y.J. Masuda, M. Bruton-Adams, C.O. Emaurois, B. Gorong, C.J. Hudlow, R. James, H. Kuhlken, B. Masike-Liri, E. Musrasrik-Carl, A. Otzelberger, K. Relang, B.M. Reyuw, B. Sigrah, C. Stinnett, J. Tellei, and L. Whitford, 2018: Raising the voices of Pacific Island women to inform climate adaptation policies. *Marine Policy*, **93**, 178–185. https://doi.org/10.1016/j.marpol.2018.03.011

112. Colin, P.L., 2018: Ocean warming and the reefs of Palau. *Oceanography*, **31** (2), 126–135. https://doi.org/10.5670/oceanog.2018.214

113. Miles, W., Z. Grecni, E.X. Matsutaro, P. Colin, V. Keener, and Y. Golbuu, 2020: Climate Change in Palau: Indicators and Considerations for Key Sectors. East-West Center, Honolulu, HI. https://doi.org/10.5281/zenodo.4124259

114. Carmona, R., J.P. MacDonald, D.S. Dorough, T.B. Rai, G.A. Sanago, and S. Thorsell, 2022: Recognising the Contributions of Indigenous Peoples in Global Climate Action? An Analysis of the IPCC Report on Impacts, Adaptation and Vulnerability. IWGIA Briefing Paper. International Work Group for Indigenous Affairs, 8 pp. https://www.iwgia.org/en/resources/publications/4621-iwgia-briefing-analysing-recognition-contrubutions-indigenous-peoples-ipcc-report.html

115. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–33. https://doi.org/10.1017/9781009325844.001

116. Farmery, A.K., K. Alexander, K. Anderson, J.L. Blanchard, C.G. Carter, K. Evans, M. Fischer, A. Fleming, S. Frusher, E.A. Fulton, B. Haas, C.K. MacLeod, L. Murray, K.L. Nash, G.T. Pecl, Y. Rousseau, R. Trebilco, I.E. van Putten, S. Mauli, L. Dutra, D. Greeno, J. Kaltavara, R. Watson, and B. Nowak, 2022: Food for all: Designing sustainable and secure future seafood systems. *Reviews in Fish Biology and Fisheries*, **32** (1), 101–121. https://doi.org/10.1007/s11160-021-09663-x

117. Iese, V., E. Holland, M. Wairiu, R. Havea, S. Patolo, M. Nishi, T. Hoponoa, R.M. Bourke, A. Dean, and L. Waqainabete, 2018: Facing food security risks: The rise and rise of the sweet potato in the Pacific Islands. *Global Food Security*, **18**, 48–56. https://doi.org/10.1016/j.gfs.2018.07.004

118. Mausio, K., T. Miura, and N.K. Lincoln, 2020: Cultivation potential projections of breadfruit (*Artocarpus altilis*) under climate change scenarios using an empirically validated suitability model calibrated in Hawai'i. *PLoS ONE*, **15** (5), 0228552. https://doi.org/10.1371/journal.pone.0228552

119. Mcleod, E., M. Bruton-Adams, J. Förster, C. Franco, G. Gaines, B. Gorong, R. James, G. Posing-Kulwaum, M. Tara, and E. Terk, 2019: Lessons from the Pacific Islands—Adapting to climate change by supporting social and ecological resilience. *Frontiers in Marine Science*, **6**, 289. https://doi.org/10.3389/fmars.2019.00289

120. Donato, D.C., J.B. Kauffman, R.A. Mackenzie, A. Ainsworth, and A.Z. Pfleeger, 2012: Whole-island carbon stocks in the tropical Pacific: Implications for mangrove conservation and upland restoration. *Journal of Environmental Management*, **97**, 89–96. https://doi.org/10.1016/j.jenvman.2011.12.004

121. Elevitch, C.R., D.N. Mazaroli, and D. Ragone, 2018: Agroforestry standards for regenerative agriculture. *Sustainability*, **10** (9). https://doi.org/10.3390/su10093337

122. Melone, A., L.L. Bremer, S.E. Crow, Z. Hastings, K.B. Winter, T. Ticktin, Y.M. Rii, M. Wong, K. Kukea-Shultz, S.J. Watson, and C. Trauernicht, 2021: Assessing baseline carbon stocks for forest transitions: A case study of agroforestry restoration from Hawai'i. *Agriculture*, **11** (3). https://doi.org/10.3390/agriculture11030189

123. Bolden, I.W., S.K. Seroy, E.A. Roberts, L. Schmeisser, J.Z. Koehn, C.H. Rilometo, E.L. Odango, C. Barros, J.P. Sachs, and T. Klinger, 2018: Climate-related community knowledge networks as a tool to increase learning in the context of environmental change. *Climate Risk Management*, **21**, 1–6. https://doi.org/10.1016/j.crm.2018.04.004

124. Frungillo, J., K. Hougen, B. Merrick, B. Rice, S. Sprague, E. Trelegan, and T.D. Zimmerman, 2022: An Educator's Guide to the Meaningful Watershed Educational Experience (MWEE). National Oceanic and Atmospheric Administration, Bay Watershed Education and Training Program. https://www.noaa.gov/office-education/bwet/resources/mwee-guide

125. HWMO, 2021: Ready, Set, Go! Hawaii: Your Personal Wildland Fire Action Guide. Hawai'i Wildlife Management Organization, 20 pp. https://www.hawaiiwildfire.org/fire-resource-library-blog/rsg-your-personal-wildland-fire-action-guide

126. Longman, R.J., A.G. Frazier, C.P. Giardina, E.W. Parsons, and S. McDaniel, 2022: The Pacific drought knowledge exchange: A co-production approach to deliver climate resources to user groups. *Sustainability*, **14** (17). https://doi.org/10.3390/su141710554

127. USGS, 2021: Pacific Islands Climate Adaptation Science Center (PICASC) K12 Education Hub. U.S. Geological Survey, accessed April 12, 2023. https://picasc-education-usgs.hub.arcgis.com/

128. Dacks, R., H. McMillen, P. Heimuli, K. Kahaleua, S. Burgess, C.P. Giardina, K. Francisco, and T. Ticktin, 2021: The important role of environmental stewardship groups in supporting human health and well-being. *Frontiers in Sustainable Cities*, **3**, 710355. https://doi.org/10.3389/frsc.2021.710355

129. Qinaʻau, J., 2016: BOE Policy E-3: Nā Hopena Aʻo (HĀ). McREL International, Honolulu, HI. https://www.hawaiipublicschools.org/doe%20forms/ha-article-july2016.pdf

130. UNDRR, 2016: UNISDR Annual Report 2015. United Nations Office for Disaster Risk Reduction, Geneva, Switzerland, 75 pp. https://www.undrr.org/publication/unisdr-annual-report-2015

131. HGG, 2022: Aloha+ Challenge: 2021 Annual Sustainability Scorecard. Hawaii Green Growth. https://alohachallenge.hawaii.gov/pages/2021-annual-sustainability-scorecard

132. Guam Green Growth, 2021: G3 Action Framework. University of Guam and Office of the Governor of Guam, Mangilao, Guam. https://guamgreengrowth.org/g3-action-framework/

133. Federated States of Micronesia, 2004: Strategic Development Plan 2004–2023. Federated States of Micronesia, Department of Environment, Climate Change, and Emergency Management. https://fsm-data.sprep.org/resource/strategic-development-plan-2004-2023

134. Gombos, M., 2020: Micronesia Challenge Evaluation: A Stakeholder-Based Review of a Pioneering Regional Conservation Initiative. Sea Change Consulting. http://www.ourmicronesia.org/strengthening-and-enabling-the-micronesia-challenge-2030.html

135. Gingerich, S.B., C.I. Voss, and A.G. Johnson, 2017: Seawater-flooding events and impact on freshwater lenses of low-lying islands: Controlling factors, basic management and mitigation. *Journal of Hydrology*, **551**, 676688. https://doi.org/10.1016/j.jhydrol.2017.03.001

136. Oberle, F.K.J., P.W. Swarzenski, and C.D. Storlazzi, 2017: Atoll groundwater movement and its response to climatic and sea-level fluctuations. *Water*, **9** (9), 650. https://doi.org/10.3390/w9090650

137. Clilverd, H.M., Y.P. Tsang, D.M. Infante, A.J. Lynch, and A.M. Strauch, 2019: Long-term streamflow trends in Hawai'i and implications for native stream fauna. *Hydrological Processes*, **33** (5), 699–719. https://doi.org/10.1002/hyp.13356

138. Bierque, E., R. Thibeaux, D. Girault, M.-E. Soupé-Gilbert, and C. Goarant, 2020: A systematic review of *Leptospira* in water and soil environments. *PLoS ONE*, **15** (1), e0227055. https://doi.org/10.1371/journal.pone.0227055

139. Economy, L.M., T.N. Wiegner, A.M. Strauch, J.D. Awaya, and T. Gerken, 2019: Rainfall and streamflow effects on estuarine *Staphylococcus aureus* and fecal indicator bacteria concentrations. *Journal of Environmental Quality*, **48** (6), 1711–1721. https://doi.org/10.2134/jeq2019.05.0196

140. Strauch, A.M., R.A. MacKenzie, G.L. Bruland, R. Tingley III, and C.P. Giardina, 2014: Climate change and land use drivers of fecal bacteria in tropical Hawaiian rivers. *Journal of Environmental Quality*, **43** (4), 1475–1483. https://doi.org/10.2134/jeq2014.01.0025

141. Strauch, A.M., R.A. MacKenzie, C.P. Giardina, and G.L. Bruland, 2018: Influence of declining mean annual rainfall on the behavior and yield of sediment and particulate organic carbon from tropical watersheds. *Geomorphology*, **306**, 28–39. https://doi.org/10.1016/j.geomorph.2017.12.030

142. Brewington, L., V. Keener, and A. Mair, 2019: Simulating land cover change impacts on groundwater recharge under selected climate projections, Maui, Hawai'i. *Remote Sensing*, **11** (24), 3048. https://doi.org/10.3390/rs11243048

143. Hejazian, M., J.J. Gurdak, P. Swarzenski, K.O. Odigie, and C.D. Storlazzi, 2017: Land-use change and managed aquifer recharge effects on the hydrogeochemistry of two contrasting atoll island aquifers, Roi-Namur Island, Republic of the Marshall Islands. *Applied Geochemistry*, **80**, 58–71. https://doi.org/10.1016/j.apgeochem.2017.03.006

144. Ghazal, K.A., O.T. Leta, A.I. El-Kadi, and H. Dulai, 2019: Assessment of wetland restoration and climate change impacts on water balance components of the Heeia coastal wetland in Hawaii. *Hydrology*, **6** (2), 37. https://doi.org/10.3390/hydrology6020037

145. Leta, O.T., A.I. El-Kadi, and H. Dulai, 2017: Implications of climate change on water budgets and reservoir water harvesting of Nuuanu area watersheds, Oahu, Hawaii. *Journal of Water Resources Planning and Management*, **143** (11), 05017013. https://doi.org/10.1061/(asce)wr.1943-5452.0000839

146. Leta, O.T., A.I. El-Kadi, and H. Dulai, 2018: Impact of climate change on daily streamflow and its extreme values in Pacific Island watersheds. *Sustainability*, **10** (6), 2057. https://doi.org/10.3390/su10062057

147. Mair, A., A.G. Johnson, K. Rotzoll, and D.S. Oki, 2019: Estimated Groundwater Recharge from a Water-Budget Model Incorporating Selected Climate Projections, Island of Maui, Hawai'i. Scientific Investigations Report 2019–5064. U.S. Geological Survey, 46 pp. https://doi.org/10.3133/sir20195064

148. Strauch, A.M., C.P. Giardina, R.A. MacKenzie, C. Heider, T.W. Giambelluca, E. Salminen, and G.L. Bruland, 2017: Modeled effects of climate change and plant invasion on watershed function across a steep tropical rainfall gradient. *Ecosystems*, **20** (3), 583–600. https://doi.org/10.1007/s10021-016-0038-3/figures/7

149. O'Connor, C.F., P.-S. Chu, P.-C. Hsu, and K. Kodama, 2015: Variability of Hawaiian winter rainfall during La Niña events since 1956. *Journal of Climate*, **28** (19), 7809–7823. https://doi.org/10.1175/jcli-d-14-00638.1

150. Stevens, L.E., R. Frankson, K.E. Kunkel, P.-S. Chu, and W. Sweet, 2022: Hawai'i State Climate Summary 2022. NOAA Technical Report NESDIS 150-HI. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD, 5 pp. https://statesummaries.ncics.org/chapter/hi/

151. Felton, D., 2021: Risks of Sea Level Rise and Increased Flooding on Known Chemical Contamination in Hawaii. Hawaii State Department of Health, Honolulu, HI. https://health.hawaii.gov/heer/files/2021/06/Climate-Change-and-Chemical-Contamination-memo-updated-June-2021.pdf

152. Denton, G.R.W., C.A. Emborski, N.C. Habana, and J.A. Starmer, 2014: Influence of urban runoff, inappropriate waste disposal practices and World War II on the heavy metal status of sediments in the southern half of Saipan Lagoon, Saipan, CNMI. *Marine Pollution Bulletin*, **81** (1), 276–281. https://doi.org/10.1016/j.marpolbul.2014.01.014

153. Nakama, R.K., J.N. Mitchell, and D.S. Oki, 2022: December 23, 2021, Red Hill Synoptic Groundwater-Level Survey, Hālawa Area, O'ahu, Hawai'i. USGS Open-File Report 2022-1018. U.S. Geological Survey, Reston, VA, 10 pp. https://doi.org/10.3133/ofr20221018

154. Jarsjö, J., Y. Andersson-Sköld, M. Fröberg, J. Pietroń, R. Borgström, Å. Löv, and D.B. Kleja, 2020: Projecting impacts of climate change on metal mobilization at contaminated sites: Controls by the groundwater level. *Science of The Total Environment*, **712**, 135560. https://doi.org/10.1016/j.scitotenv.2019.135560

155. Kibria, G., D. Nugegoda, G. Rose, and A.K.Y. Haroon, 2021: Climate change impacts on pollutants mobilization and interactive effects of climate change and pollutants on toxicity and bioaccumulation of pollutants in estuarine and marine biota and linkage to seafood security. *Marine Pollution Bulletin*, **167**, 112364. https://doi.org/10.1016/j.marpolbul.2021.112364

156. Alsumaiei, A.A. and R.T. Bailey, 2018: Quantifying threats to groundwater resources in the Republic of Maldives Part II: Recovery from tsunami marine overwash events. *Hydrological Processes*, **32** (9), 1154–1165. https://doi.org/10.1002/hyp.11473

157. Babu, R., N. Park, and B. Nam, 2020: Regional and well-scale indicators for assessing the sustainability of small island fresh groundwater lenses under future climate conditions. *Environmental Earth Sciences*, **79** (1), 47. https://doi.org/10.1007/s12665-019-8773-3

158. Lassiter, A., 2021: Rising seas, changing salt lines, and drinking water salinization. *Current Opinion in Environmental Sustainability*, **50**, 208–214. https://doi.org/10.1016/j.cosust.2021.04.009

159. Post, V.E.A., A.L. Bosserelle, S.C. Galvis, P.J. Sinclair, and A.D. Werner, 2018: On the resilience of small-island freshwater lenses: Evidence of the long-term impacts of groundwater abstraction on Bonriki Island, Kiribati. *Journal of Hydrology*, **564**, 133–148. https://doi.org/10.1016/j.jhydrol.2018.06.015

160. Yang, J., H. Zhang, X. Yu, T. Graf, and H.A. Michael, 2018: Impact of hydrogeological factors on groundwater salinization due to ocean-surge inundation. *Advances in Water Resources*, **111**, 423–434. https://doi.org/10.1016/j.advwatres.2017.11.017

161. Povak, N.A., C.P. Giardina, P.F. Hessburg, K.M. Reynolds, R.B. Salter, C. Heider, E. Salminen, and R. MacKenzie, 2020: A decision support tool for the conservation of tropical forest and nearshore environments on Babeldaob Island, Palau. *Forest Ecology and Management*, **476**, 118480. https://doi.org/10.1016/j.foreco.2020.118480

162. DeMartini, E., P. Jokiel, J. Beets, Y. Stender, C. Storlazzi, D. Minton, and E. Conklin, 2013: Terrigenous sediment impact on coral recruitment and growth affects the use of coral habitat by recruit parrotfishes (*F. Scaridae*). *Journal of Coastal Conservation*, **17** (3), 417–429. https://doi.org/10.1007/s11852-013-0247-2

163. Fong, C.R., C.J. Gaynus, and R.C. Carpenter, 2020: Extreme rainfall events pulse substantial nutrients and sediments from terrestrial to nearshore coastal communities: A case study from French Polynesia. *Scientific Reports*, **10** (1), 2955. https://doi.org/10.1038/s41598-020-59807-5

164. Rodysill, J.R., J.M. Russell, M. Vuille, S. Dee, B. Lunghino, and S. Bijaksana, 2019: La Niña-driven flooding in the Indo-Pacific warm pool during the past millennium. *Quaternary Science Reviews*, **225**, 106020. https://doi.org/10.1016/j.quascirev.2019.106020

165. Andrew, N.L., E.H. Allison, T. Brewer, J. Connell, H. Eriksson, J.G. Eurich, A. Farmery, J.A. Gephart, C.D. Golden, M. Herrero, K. Mapusua, K.L. Seto, M.K. Sharp, P. Thornton, A.M. Thow, and J. Tutuo, 2022: Continuity and change in the contemporary Pacific food system. *Global Food Security*, **32**, 100608. https://doi.org/10.1016/j.gfs.2021.100608

166. Davis, K.F., S. Downs, and J.A. Gephart, 2021: Towards food supply chain resilience to environmental shocks. *Nature Food*, **2** (1), 54–65. https://doi.org/10.1038/s43016-020-00196-3

167. Dyer, J., 2017: Ch. 12. Adapting climate change projections to Pacific maritime supply chains. In: *Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life*. Leal Filho, W., Ed. Springer, Cham, Switzerland, 199–223. https://doi.org/10.1007/978-3-319-50094-2_12

168. Friel, S., A. Schram, and B. Townsend, 2020: The nexus between international trade, food systems, malnutrition and climate change. *Nature Food*, **1** (1), 51–58. https://doi.org/10.1038/s43016-019-0014-0

169. Tigchelaar, M., W.W.L. Cheung, E.Y. Mohammed, M.J. Phillips, H.J. Payne, E.R. Selig, C.C.C. Wabnitz, M.A. Oyinlola, T.L. Frölicher, J.A. Gephart, C.D. Golden, E.H. Allison, A. Bennett, L. Cao, J. Fanzo, B.S. Halpern, V.W.Y. Lam, F. Micheli, R.L. Naylor, U.R. Sumaila, A. Tagliabue, and M. Troell, 2021: Compound climate risks threaten aquatic food system benefits. *Nature Food*, **2** (9), 673–682. https://doi.org/10.1038/s43016-021-00368-9

170. Allen, M.G., 2015: Framing food security in the Pacific Islands: Empirical evidence from an island in the Western Pacific. *Regional Environmental Change*, **15** (7), 1341–1353. https://doi.org/10.1007/s10113-014-0734-5

171. Campbell, J., 2015: Development, global change and traditional food security in Pacific Island countries. *Regional Environmental Change*, **15**, 1313–1324. https://doi.org/10.1007/s10113-014-0697-6

172. Charlton, K.E., J. Russell, E. Gorman, Q. Hanich, A. Delisle, B. Campbell, and J. Bell, 2016: Fish, food security and health in Pacific Island countries and territories: A systematic literature review. *BMC Public Health*, **16** (1), 285. https://doi.org/10.1186/s12889-016-2953-9

173. Connell, J., 2020: Ch. 4. Lost roots? Fading food security in Micronesia. In: *Food Security in Small Island States*. Connell, J. and K. Lowitt, Eds. Springer, Singapore, 57–76. https://doi.org/10.1007/978-981-13-8256-7_4

174. Perroy, R.L., J. Melrose, and S. Cares, 2016: The evolving agricultural landscape of post-plantation Hawai'i. *Applied Geography*, **76**, 154–162. https://doi.org/10.1016/j.apgeog.2016.09.018

175. Farrell, P., A.M. Thow, J.T. Wate, N. Nonga, P. Vatucawaqa, T. Brewer, M.K. Sharp, A. Farmery, H. Trevena, E. Reeve, H. Eriksson, I. Gonzalez, G. Mulcahy, J.G. Eurich, and N.L. Andrew, 2020: COVID-19 and Pacific food system resilience: Opportunities to build a robust response. *Food Security*, **12** (4), 783–791. https://doi.org/10.1007/s12571-020-01087-y

176. Kim, K. and L. Bui, 2019: Learning from Hurricane Maria: Island ports and supply chain resilience. *International Journal of Disaster Risk Reduction*, **39**, 101244. https://doi.org/10.1016/j.ijdrr.2019.101244

177. Eddy, T.D., V.W.Y. Lam, G. Reygondeau, A.M. Cisneros-Montemayor, K. Greer, M.L.D. Palomares, J.F. Bruno, Y. Ota, and W.W.L. Cheung, 2021: Global decline in capacity of coral reefs to provide ecosystem services. *One Earth*, **4** (9), 1278–1285. https://doi.org/10.1016/j.oneear.2021.08.016

178. Gillett, R., 2016: *Fisheries in the Economies of Pacific Island Countries and Territories*, 2nd ed. Pacific Community, Noumea, New Caledonia. https://www.spc.int/sites/default/files/wordpresscontent/wp-content/uploads/2016/11/Gillett_16_Benefish-fisheries-in-economies-of-pacific-countries.pdf

179. Munday, P.L., G.P. Jones, M.S. Pratchett, and A.J. Williams, 2008: Climate change and the future for coral reef fishes. *Fish and Fisheries*, **9** (3), 261–285. https://doi.org/10.1111/j.1467-2979.2008.00281.x

180. Pippard, H., G.M. Ralph, M.S. Harvey, K.E. Carpenter, J.R. Buchanan, D.W. Greenfield, H.D. Harwell, H.K. Larson, A. Lawrence, C. Linardich, K. Matsuura, H. Motomura, T.A. Munroe, R.F. Myers, B.C. Russell, W.F. Smith-Vaniz, J.-C. Vié, R.R. Thaman, and J.T. Williams, 2017: The Conservation Status of Marine Biodiversity of the Pacific Islands of Oceania. IUCN International Union for Conservation of Nature. https://doi.org/10.2305/iucn.ch.2017.04.en

181. Bell, J.D., V. Allain, E.H. Allison, S. Andréfouët, N.L. Andrew, M.J. Batty, M. Blanc, J.M. Dambacher, J. Hampton, Q. Hanich, S. Harley, A. Lorrain, M. McCoy, N. McTurk, S. Nicol, G. Pilling, D. Point, M.K. Sharp, P. Vivili, and P. Williams, 2015: Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. *Marine Policy*, **51**, 584–591. https://doi.org/10.1016/j.marpol.2014.10.005

182. Maire, E., N.A.J. Graham, M.A. MacNeil, V.W.Y. Lam, J.P.W. Robinson, W.W.L. Cheung, and C.C. Hicks, 2021: Micronutrient supply from global marine fisheries under climate change and overfishing. *Current Biology*, **31** (18), 4132–4138. https://doi.org/10.1016/j.cub.2021.06.067

183. Bell, J.D., M. Kronen, A. Vunisea, W.J. Nash, G. Keeble, A. Demmke, S. Pontifex, and S. Andréfouët, 2009: Planning the use of fish for food security in the Pacific. *Marine Policy*, **33** (1), 64–76. https://doi.org/10.1016/j.marpol.2008.04.002

184. Grafeld, S., K.L.L. Oleson, L. Teneva, and J.N. Kittinger, 2017: Follow that fish: Uncovering the hidden blue economy in coral reef fisheries. *PLoS ONE*, **12** (8), e0182104. https://doi.org/10.1371/journal.pone.0182104

185. McCoy, K.S., I.D. Williams, A.M. Friedlander, H. Ma, L. Teneva, and J.N. Kittinger, 2018: Estimating nearshore coral reef-associated fisheries production from the main Hawaiian Islands. *PLoS ONE*, **13** (4), e0195840. https://doi.org/10.1371/journal.pone.0195840

186. Teneva, L.T., E. Schemmel, and J.N. Kittinger, 2018: State of the plate: Assessing present and future contribution of fisheries and aquaculture to Hawai'i's food security. *Marine Policy*, **94**, 28–38. https://doi.org/10.1016/j.marpol.2018.04.025

187. Hanich, Q., C.C.C. Wabnitz, Y. Ota, M. Amos, C. Donato-Hunt, and A. Hunt, 2018: Small-scale fisheries under climate change in the Pacific Islands region. *Marine Policy*, **88**, 279–284. https://doi.org/10.1016/j.marpol.2017.11.011

188. Galappaththi, E.K., S.T. Ichien, A.A. Hyman, C.J. Aubrac, and J.D. Ford, 2020: Climate change adaptation in aquaculture. *Reviews in Aquaculture*, **12** (4), 2160–2176. https://doi.org/10.1111/raq.12427

189. Oyinlola, M.A., G. Reygondeau, C.C.C. Wabnitz, and W.W.L. Cheung, 2020: Projecting global mariculture diversity under climate change. *Global Change Biology*, **26** (4), 2134–2148. https://doi.org/10.1111/gcb.14974

190. Bell, J. and M. Taylor, 2015: Building Climate-Resilient Food Systems for Pacific Islands. Program Report 2015-15. WorldFish, Penang, Malaysia. https://hdl.handle.net/20.500.12348/214

191. Bell, J., M. Taylor, M. Amos, and N. Andrew, 2016: Climate Change and Pacific Island Food Systems: The Future of Food, Farming and Fishing in the Pacific Islands under a Changing Climate. University of Wollongong, Australia. https://ro.uow.edu.au/lhapapers/3271/

192. Golden, C.D., E.H. Allison, W.W.L. Cheung, M.M. Dey, B.S. Halpern, D.J. McCauley, M. Smith, B. Vaitla, D. Zeller, and S.S. Myers, 2016: Nutrition: Fall in fish catch threatens human health. *Nature*, **534** (7607), 317–320. https://doi.org/10.1038/534317a

193. Ann Singeo (Author), March 15, 2022: Oral communication with Ngarchelong, Palau fishermen, Tino Kloulechad.

194. Akutagawa, M., H. Williams, S. Kamakaʻala, D.-R. Gibson, M. Kaʻaihue, K. King-Hinds, O. Manglona, K. Nakoa, K. Rawlins-Fernandez, K. Rivera, L.R. Kaʻaekuahiwi, T. Stevenson, and L. Yang, 2016: Traditional & Customary Practices Report for Manaʻe, Molokaʻi: Traditional Subsistence Uses, Mālama Practices and Recommendations, and Native Hawaiian Rights Protections of Kamaʻāina Families of Manaʻe Moku, East Molokaʻi, Hawaiʻi. Office of Hawaiian Affairs. https://doi.org/10.13140/rg.2.1.2697.5125

195. Sterling, E.J., C. Filardi, A. Toomey, A. Sigouin, E. Betley, N. Gazit, J. Newell, S. Albert, D. Alvira, N. Bergamini, M. Blair, D. Boseto, K. Burrows, N. Bynum, S. Caillon, J.E. Caselle, J. Claudet, G. Cullman, R. Dacks, P.B. Eyzaguirre, S. Gray, J. Herrera, P. Kenilorea, K. Kinney, N. Kurashima, S. Macey, C. Malone, S. Mauli, J. McCarter, H. McMillen, P.a. Pascua, P. Pikacha, A.L. Porzecanski, P. de Robert, M. Salpeteur, M. Sirikolo, M.H. Stege, K. Stege, T. Ticktin, R. Vave, A. Wali, P. West, K.B. Winter, and S.D. Jupiter, 2017: Biocultural approaches to well-being and sustainability indicators across scales. *Nature Ecology & Evolution*, **1** (12), 1798–1806. https://doi.org/10.1038/s41559-017-0349-6

196. Iese, V., S. Halavatau, A.D.R. N'Yeurt, M. Wairiu, E. Holland, A. Dean, F. Veisa, S. Patolo, R. Havea, S. Bosenaqali, and O. Navunicagi, 2020: Ch. 9. Agriculture under a changing climate. In: *Climate Change and Impacts in the Pacific*. Kumar, L., Ed. Springer, Cham, Switzerland, 323–357. https://doi.org/10.1007/978-3-030-32878-8_9

197. Rosegrant, M.W., R.A. Valmonte-Santos, T. Thomas, L. You, and C.A. Chiang, 2015: Climate Change, Food Security, and Socioeconomic Livelihood in Pacific Islands. Asian Development Bank and International Food Policy Research Institute. https://www.adb.org/publications/climate-change-food-security-socioeconomic-livelihood-pacific

198. Palanivel, H. and S. Shah, 2021: Unlocking the inherent potential of plant genetic resources: Food security and climate adaptation strategy in Fiji and the Pacific. *Environment, Development and Sustainability*, **23** (10), 14264–14323. https://doi.org/10.1007/s10668-021-01273-8

199. Golden, C.D., J.Z. Koehn, A. Shepon, S. Passarelli, C.M. Free, D.F. Viana, H. Matthey, J.G. Eurich, J.A. Gephart, E. Fluet-Chouinard, E.A. Nyboer, A.J. Lynch, M. Kjellevold, S. Bromage, P. Charlebois, M. Barange, S. Vannuccini, L. Cao, K.M. Kleisner, E.B. Rimm, G. Danaei, C. DeSisto, H. Kelahan, K.J. Fiorella, D.C. Little, E.H. Allison, J. Fanzo, and S.H. Thilsted, 2021: Aquatic foods to nourish nations. *Nature*, **598** (7880), 315–320. https://doi.org/10.1038/s41586-021-03917-1

200. MacFarland, K., C. Elevitch, J.B. Friday, K. Friday, F.K. Lake, and D. Zamora, 2017: Ch. 5. Human dimensions of agroforestry systems. In: *Agroforestry: Enhancing Resiliency in U.S. Agricultural Landscapes Under Changing Conditions*. Schoeneberger, M.M., G. Bentrup, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Washington, DC, 73–90. https://www.fs.usda.gov/research/treesearch/55790

201. McMillen, H.L., T. Ticktin, A. Friedlander, S.D. Jupiter, R. Thaman, J. Campbell, J. Veitayaki, T. Giambelluca, S. Nihmei, E. Rupeni, L. Apis-Overhoff, W. Aalbersberg, and D.F. Orcherton, 2014: Small islands, valuable insights: Systems of customary resource use and resilience to climate change in the Pacific. *Ecology and Society*, **19** (4). https://doi.org/10.5751/es-06937-190444

202. Bremer, L.L., K. Falinski, C. Ching, C.A. Wada, K.M. Burnett, K. Kukea-Shultz, N. Reppun, G. Chun, K.L.L. Oleson, and T. Ticktin, 2018: Biocultural restoration of traditional agriculture: Cultural, environmental, and economic outcomes of Lo'i Kalo restoration in He'eia, O'ahu. *Sustainability*, **10** (12), 4502. https://doi.org/10.3390/su10124502

203. Winter, K.B., Y.M. Rii, F.A.W.L. Reppun, K.D. Hintzen, R.A. Alegado, B.W. Bowen, L.L. Bremer, M. Coffman, J.L. Deenik, M.J. Donahue, K.A. Falinski, K. Frank, E.C. Franklin, N. Kurashima, N.K. Lincoln, E.M.P. Madin, M.A. McManus, C.E. Nelson, R. Okano, A. Olegario, P. Pascua, K.L.L. Oleson, M.R. Price, M.A.J. Rivera, K.S. Rodgers, T. Ticktin, C.L. Sabine, C.M. Smith, A. Hewett, R. Kaluhiwa, M. Cypher, B. Thomas, J.-A. Leong, K. Kekuewa, J. Tanimoto, K. Kukea-Shultz, A.H. Kawelo, K. Kotubetey, B.J. Neilson, T.S. Lee, and R.J. Toonen, 2020: Collaborative research to inform adaptive comanagement: A framework for the He'eia National Estuarine Research Reserve. *Ecology and Society*, **25** (4), 15. https://doi.org/10.5751/es-11895-250415

204. Fardkhales, S.A. and N. Lincoln, 2021: Food hubs play an essential role in the COVID-19 response in Hawai'i. *Journal of Agriculture, Food Systems, and Community Development*, **10** (2), 53–70. https://doi.org/10.5304/jafscd.2021.102.036

205. Ferguson, C.E., T. Tuxson, S. Mangubhai, S. Jupiter, H. Govan, V. Bonito, S. Alefaio, M. Anjiga, J. Booth, T. Boslogo, D. Boso, A. Brenier, A. Caginitoba, A. Ciriyawa, J.B. Fahai'ono, M. Fox, A. George, H. Eriksson, A. Hughes, and M. Waide, 2022: Local practices and production confer resilience to rural Pacific food systems during the COVID-19 pandemic. *Marine Policy*, **137**, 104954. https://doi.org/10.1016/j.marpol.2022.104954

206. Falanruw, M.V.C., R.M. Perkins, and F. Ruegorong, 2019: Ch. 4. Integrating traditional knowledge and geospatial science to address food security and sustaining biodiversity in Yap Islands, Micronesia. In: *Societal Dimensions of Environmental Science*. CRC Press, 79–116. https://doi.org/10.1201/9781315166827-4

207. IPIF, 2020: Partners in Science. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, the Institute of Pacific Islands Forestry, and the U.S.-Affiliated Pacific Islands. https://www.climatehubs.usda.gov/sites/default/files/psw_2020_PartnersInScience.pdf

208. Del Rosario, A.G., N.M. Esguerra, and T. Taro, 2015: *Taro Production in Palau*. College of Micronesia Land Grant Programs, 92 pp. https://chm.cbd.int/api/v2013/documents/9A9CE38C-FA3A-4CCB-F77D-EB22E815335B/attachments/212244/Taro-Production_final-2015-optimized.pdf

209. Aluli, N.E. and D.P. McGregor, 2007: 'Aina: Ke Ola O Na Kanaka 'Oiwi Land: The Health of Native Hawaiians. U.S. Department of Health and Human Services, 15 pp. https://www.nlm.nih.gov/exhibition/avoyagetohealth/pdf/LandandHealth.pdf

210. Redvers, N., Y. Celidwen, C. Schultz, O. Horn, C. Githaiga, M. Vera, M. Perdrisat, L. Mad Plume, D. Kobei, M.C. Kain, A. Poelina, J.N. Rojas, and B.S. Blondin, 2022: The determinants of planetary health: An Indigenous consensus perspective. *The Lancet Planetary Health*, **6** (2), 156–163. https://doi.org/10.1016/s2542-5196(21)00354-5

211. World Health Organization, Food and Agriculture Organization of the United Nations, and World Organisation for Animal Health, 2019: *Taking a Multisectoral, One Health Approach: A Tripartite Guide to Addressing Zoonotic Diseases in Countries*. World Health Organization, 151 pp. https://apps.who.int/iris/handle/10665/325620

212. PIFS, 2020: Kainaki II Declaration for Urgent Climate Action Now: Securing the Future of Our Blue Pacific. Pacific Islands Forum Secretariat. https://www.forumsec.org/2020/11/11/kainaki/

213. Ford, J.D., 2012: Indigenous health and climate change. *American Journal of Public Health*, **102** (7), 1260–1266. https://doi.org/10.2105/ajph.2012.300752

214. HDC, 2020: ALICE in Hawaii: A Financial Hardship Study, Aloha United Way. Hawai'i Data Collaborative, 2 pp. https://www.auw.org/alice-initiative

215. Emanuel, K., 2020: Evidence that hurricanes are getting stronger. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (24), 13194–13195. https://doi.org/10.1073/pnas.2007742117

216. Kossin, J.P., K.R. Knapp, T.L. Olander, and C.S. Velden, 2020: Global increase in major tropical cyclone exceedance probability over the past four decades. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (22), 11975–11980. https://doi.org/10.1073/pnas.1920849117

217. Stanke, C., M. Kerac, C. Prudhomme, J.M. Medlock, and V. Murray, 2013: Health effects of drought: A systematic review of the evidence. *PLoS Currents*, **5**. https://www.ncbi.nlm.nih.gov/pmc/articles/pmc3682759/

218. Reguero, B.G., C.D. Storlazzi, A.E. Gibbs, J.B. Shope, A.D. Cole, K.A. Cumming, and M.W. Beck, 2021: The value of US coral reefs for flood risk reduction. *Nature Sustainability*, **4** (8), 688–698. https://doi.org/10.1038/s41893-021-00706-6

219. Vitousek, S., P.L. Barnard, C.H. Fletcher, N. Frazer, L. Erikson, and C.D. Storlazzi, 2017: Doubling of coastal flooding frequency within decades due to sea-level rise. *Scientific Reports*, **7** (1), 1399. https://doi.org/10.1038/s41598-017-01362-7

220. Romanello, M., A. McGushin, C. Di Napoli, P. Drummond, N. Hughes, L. Jamart, H. Kennard, P. Lampard, B. Solano Rodriguez, N. Arnell, S. Ayeb-Karlsson, K. Belesova, W. Cai, D. Campbell-Lendrum, S. Capstick, J. Chambers, L. Chu, L. Ciampi, C. Dalin, N. Dasandi, S. Dasgupta, M. Davies, P. Dominguez-Salas, R. Dubrow, K.L. Ebi, M. Eckelman, P. Ekins, L.E. Escobar, L. Georgeson, D. Grace, H. Graham, S.H. Gunther, S. Hartinger, K. He, C. Heaviside, J. Hess, S.-C. Hsu, S. Jankin, M.P. Jimenez, I. Kelman, G. Kiesewetter, P.L. Kinney, T. Kjellstrom, D. Kniveton, J.K.W. Lee, B. Lemke, Y. Liu, Z. Liu, M. Lott, R. Lowe, J. Martinez-Urtaza, M. Maslin, L. McAllister, C. McMichael, Z. Mi, J. Milner, K. Minor, N. Mohajeri, M. Moradi-Lakeh, K. Morrissey, S. Munzert, K.A. Murray, T. Neville, M. Nilsson, N. Obradovich, M.O. Sewe, T. Oreszczyn, M. Otto, F. Owfi, O. Pearman, D. Pencheon, M. Rabbaniha, E. Robinson, J. Rocklöv, R.N. Salas, J.C. Semenza, J. Sherman, L. Shi, M. Springmann, M. Tabatabaei, J. Taylor, J. Trinanes, J. Shumake-Guillemot, B. Vu, F. Wagner, P. Wilkinson, M. Winning, M. Yglesias, S. Zhang, P. Gong, H. Montgomery, A. Costello, and I. Hamilton, 2021: The 2021 report of the Lancet Countdown on health and climate change: Code red for a healthy future. *The Lancet*, **398** (10311), 1619–1662. https://doi.org/10.1016/s0140-6736(21)01787-6

221. WMO, 2021: WMO Atlas of Mortality and Economic Losses From Weather, Climate and Water Extremes (1970–2019). WMO-No. 1267. World Meteorological Organization, Geneva, Switzerland. https://library.wmo.int/index.php?lvl=notice_display&id=21930#.y437p-zmjpq

222. Kishore, N., D. Marqués, A. Mahmud, M.V. Kiang, I. Rodriguez, A. Fuller, P. Ebner, C. Sorensen, F. Racy, J. Lemery, L. Maas, J. Leaning, R.A. Irizarry, S. Balsari, and C.O. Buckee, 2018: Mortality in Puerto Rico after Hurricane Maria. *New England Journal of Medicine*, **379** (2), 162–170. https://doi.org/10.1056/nejmsa1803972

223. Greene, R. and R. Skeele, 2014: Climate Change Vulnerability Assessment for the Island of Saipan, CNMI. Commonwealth of the Northern Mariana Islands Office of the Governor, Division of Coastal Resources Management, Saipan, 102 pp. https://www.doi.gov/sites/doi.gov/files/cnmi-saipan-vulnerability-assessment.pdf

224. ASCE, 2020: 2019 Hawaii Infrastructure Report Card. American Society Civil Engineers, 65 pp. https://infrastructurereportcard.org/state-item/hawaii/

225. Bell, J.E., S.C. Herring, L. Jantarasami, C. Adrianopoli, K. Benedict, K. Conlon, V. Escobar, J. Hess, J. Luvall, C.P. Garcia-Pando, D. Quattrochi, J. Runkle, and C.J. Schreck III, 2016: Ch. 4. Impacts of extreme events on human health. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 99–128. https://doi.org/10.7930/j0bz63zv

226. Britton, E. and P. Howden-Chapman, 2011: The effect of climate change on children living on Pacific Islands. In: *Climate Change and Rural Child Health*. Bell, E., B.M. Seidel, and J. Merrick, Eds. Nova Science Publishers, New York. https://www.researchgate.net/publication/330658034_The_effect_of_climate_change_on_children_living_on_pacific_islands

227. McIver, L., R. Kim, A. Woodward, S. Hales, J. Spickett, D. Katscherian, M. Hashizume, Y. Honda, H. Kim, S. Iddings, J. Naicker, H. Bambrick, A.J. McMichael, and K.L. Ebi, 2016: Health impacts of climate change in Pacific Island countries: A regional assessment of vulnerabilities and adaptation priorities. *Environmental Health Perspectives*, **124** (11), 1707–1714. https://doi.org/10.1289/ehp.1509756

228. RMI and UNICEF, 2017: Republic of the Marshall Islands Integrated Child Health and Nutrition Survey 2017, Final Report. Republic of the Marshall Islands and United Nations Children's Fund, Majuro, RMI. https://www.unicef.org/pacificislands/reports/republic-marshall-islands-integrated-child-health-and-nutrition-survey-2017-report

229. Dendy, J., D. Mesubed, P.L. Colin, C.P. Giardina, S. Cordell, T. Holm, and A. Uowolo, 2022: Dynamics of anthropogenic wildfire on Babeldaob Island (Palau) as revealed by fire history. *Fire*, **5** (2), 45. https://doi.org/10.3390/fire5020045

230. Minton, D., 2006: Fire, Erosion, and Sedimentation in the Asan-Piti Watershed and War in the Pacific NHP, Guam. PCSU Technical Report, 150. University of Hawaii at Manoa, Department of Botany, Pacific Cooperative Studies Unit, Honolulu, HI. http://hdl.handle.net/10125/836

231. Trauernicht, C., 2017: Wildfire in the Western Pacific, PFX Fact Sheet. Pacific Fire Exchange, Joint Fire Science Program. http://www.c4gts.org/wp-content/uploads/2020/05/Wildfire-in-US-Pacific-Pacific-Fire-Exchange-Fact-Sheet_Final.pdf

232. Fann, N., T. Brennan, P. Dolwick, J.L. Gamble, V. Ilacqua, L. Kolb, C.G. Nolte, T.L. Spero, and L. Ziska, 2016: Ch. 3. Air quality impacts. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 69–98. https://doi.org/10.7930/j0gq6vp6

233. McElfish, P.A., A. Chughtai, L.K. Low, R. Garner, and R.S. Purvis, 2020: 'Just doing the best we can': Health care providers' perceptions of barriers to providing care to Marshallese patients in Arkansas. *Ethnicity & Health*, **25** (7), 1004–1017. https://doi.org/10.1080/13557858.2018.1471670

234. McElfish, P.A., E. Hallgren, and S. Yamada, 2015: Effect of US health policies on health care access for Marshallese migrants. *American Journal of Public Health*, **105** (4), 637–643. https://doi.org/10.2105/ajph.2014.302452

235. Adger, W.N., J. Barnett, K. Brown, N. Marshall, and K. O'Brien, 2013: Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, **3** (2), 112–117. https://doi.org/10.1038/nclimate1666

236. Rice, S.M. and L.J. McIver, 2016: Climate change and mental health: Rationale for research and intervention planning. *Asian Journal of Psychiatry*, **20**, 1–2. https://doi.org/10.1016/j.ajp.2015.12.011

237. Tiatia-Seath, J., T. Tupou, and I. Fookes, 2020: Climate change, mental health, and well-being for Pacific peoples: A literature review. *The Contemporary Pacific*, **32** (2), 399–430. https://doi.org/10.1353/cp.2020.0035

238. Asugeni, J., D. MacLaren, P.D. Massey, and R. Speare, 2015: Mental health issues from rising sea level in a remote coastal region of the Solomon Islands: Current and future. *Australasian Psychiatry*, **23** (supp_6), 22–25. https://doi.org/10.1177/1039856215609767

239. Gibson, K., N. Haslam, and I. Kaplan, 2019: Distressing encounters in the context of climate change: Idioms of distress, determinants, and responses to distress in Tuvalu. *Transcultural Psychiatry*, **56** (4), 667–696. https://doi.org/10.1177/1363461519847057

240. OBrien, L.V., H.L. Berry, C. Coleman, and I.C. Hanigan, 2014: Drought as a mental health exposure. *Environmental Research*, **131**, 181–187. https://doi.org/10.1016/j.envres.2014.03.014

241. Gray, N.A., M. Wolley, A. Liew, and M. Nakayama, 2015: Natural disasters and dialysis care in the Asia-Pacific. *Nephrology*, **20** (12), 873–880. https://doi.org/10.1111/nep.12522

242. Speldewinde, P.C., A. Cook, P. Davies, and P. Weinstein, 2009: A relationship between environmental degradation and mental health in rural Western Australia. *Health & Place*, **15** (3), 880–887. https://doi.org/10.1016/j.healthplace.2009.02.011

243. Stillman, S., D. McKenzie, and J. Gibson, 2009: Migration and mental health: Evidence from a natural experiment. *Journal of Health Economics*, **28** (3), 677–687. https://doi.org/10.1016/j.jhealeco.2009.02.007

244. Mental Health and Addiction Inquiry, 2018: He Ara Oranga: Report of the Government Inquiry into Mental Health and Addiction. New Zealand Government, Government Inquiry into Mental Health and Addiction. https://mentalhealth.inquiry.govt.nz/inquiry-report/he-ara-oranga/

245. Cao-Lormeau, V., 2016: Tropical islands as new hubs for emerging arboviruses. *Emerging Infectious Diseases*, **22** (5), 913–915. https://doi.org/10.3201/eid2205.150547

246. Matthews, R.J., I. Kaluthotage, T.L. Russell, T.B. Knox, P.F. Horwood, and A.T. Craig, 2022: Arboviral disease outbreaks in the Pacific Islands countries and areas, 2014 to 2020: A systematic literature and document review. *Pathogens*, **11** (1), 74. https://doi.org/10.3390/pathogens11010074

247. Filho, W.L., S. Scheday, J. Boenecke, A. Gogoi, A. Maharaj, and S. Korovou, 2019: Climate change, health and mosquito-borne diseases: Trends and implications to the Pacific region. *International Journal of Environmental Research and Public Health*, **16** (24), 5114. https://doi.org/10.3390/ijerph16245114

248. PIHOA, 2022: PIHOA Executive Director and Board Vice President Meet with the US Department of State at the Our Ocean Conference in Palau. Pacific Island Health Officers' Association. https://www.pihoa.org/pihoa-executive-director-and-board-vice-president-meet-with-the-us-department-of-state-at-the-our-ocean-conference-in-palau/

249. Kulkarni, M.A., C. Duguay, and K. Ost, 2022: Charting the evidence for climate change impacts on the global spread of malaria and dengue and adaptive responses: A scoping review of reviews. *Globalization and Health*, **18** (1), 1. https://doi.org/10.1186/s12992-021-00793-2

250. CAPA Strategies, 2019: Heat Watch Report. CAPA Strategies Heat Watch Program, Honolulu, HI. https://static1.squarespace.com/static/5e3885654a153a6ef84e6c9c/t/5ee82d0676556f740fa0ef0a/1592274200546/community+heat+assessment+preliminary+report-honolulu_dec_2019-lores.pdf

251. CCH OCCSR, 2019: Oʻahu Community Heat Map. City and County of Honolulu, Office of Climate Change, Sustainability and Resiliency. https://cchnl.maps.arcgis.com/apps/View/index.html?appid=ff1b73d836074cf6b2aca420fffbd930

252. Vicedo-Cabrera, A.M., N. Scovronick, F. Sera, D. Royé, R. Schneider, A. Tobias, C. Astrom, Y. Guo, Y. Honda, D.M. Hondula, R. Abrutzky, S. Tong, M.d.S.Z.S. Coelho, P.H.N. Saldiva, E. Lavigne, P.M. Correa, N.V. Ortega, H. Kan, S. Osorio, J. Kyselý, A. Urban, H. Orru, E. Indermitte, J.J.K. Jaakkola, N. Ryti, M. Pascal, A. Schneider, K. Katsouyanni, E. Samoli, F. Mayvaneh, A. Entezari, P. Goodman, A. Zeka, P. Michelozzi, F. de'Donato, M. Hashizume, B. Alahmad, M.H. Diaz, C.D.L.C. Valencia, A. Overcenco, D. Houthuijs, C. Ameling, S. Rao, F. Di Ruscio, G. Carrasco-Escobar, X. Seposo, S. Silva, J. Madureira, I.H. Holobaca, S. Fratianni, F. Acquaotta, H. Kim, W. Lee, C. Iniguez, B. Forsberg, M.S. Ragettli, Y.L.L. Guo, B.Y. Chen, S. Li, B. Armstrong, A. Aleman, A. Zanobetti, J. Schwartz, T.N. Dang, D.V. Dung, N. Gillett, A. Haines, M. Mengel, V. Huber, and A. Gasparrini, 2021: The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, **11** (6), 492–500. https://doi.org/10.1038/s41558-021-01058-x

253. Choudhary, E., T.H. Chen, C. Martin, S. Vagi, J. Roth, M. Keim, R. Noe, S.E. Ponausuia, S. Lemusu, T. Bayleyegn, and A. Wolkin, 2012: Public health needs assessments of Tutuila Island, American Samoa, after the 2009 tsunami. *Disaster Medicine and Public Health Preparedness*, **6** (3), 209–216. https://doi.org/10.1001/dmp.2012.40

254. Ichiho, H.M. and N. Aitaoto, 2013: Assessing the system of services for chronic diseases prevention and control in the US-affiliated Pacific Islands: Introduction and methods. *Hawai'i Journal of Medicine & Public Health*, **72** (5), 5–9. https://www.ncbi.nlm.nih.gov/pmc/articles/pmc3689456/

255. Sievert, K., M. Lawrence, A. Naika, and P. Baker, 2019: Processed foods and nutrition transition in the Pacific: Regional trends, patterns and food system drivers. *Nutrients*, **11** (6), 1328. https://doi.org/10.3390/nu11061328

256. SPC, 2019: Pacific Community Results Report: 2018. Pacific Community, Noumea, New Caledonia. https://www.spc.int/updates/blog/2019/07/pacific-community-results-report-2018-year-in-review

257. Novotny, R., M.K. Fialkowski, F. Li, Y. Paulino, D. Vargo, R. Jim, P. Coleman, A. Bersamin, C.R. Nigg, R.T.L. Guerrero, J. Deenik, J.H. Kim, and L.R. Wilkens, 2015: Systematic review of prevalence of young child overweight and obesity in the United States–Affiliated Pacific region compared with the 48 contiguous states: The children's healthy living program. *American Journal of Public Health*, **105** (1), 22–35. https://doi.org/10.2105/ajph.2014.302283

258. Buehler, J., 2020: The storm, the flood, and the future. *Ka Pili Kai Kau.* https://seagrant.soest.hawaii.edu/the-storm-the-flood-and-the-future/

259. Leenders, N., P. Holland, and P. Taylor, 2017: Post Disaster Needs Assessment of the 2015-2016 Drought. Republic of the Marshall Islands. https://www.ilo.org/wcmsp5/groups/public/---ed_emp/documents/publication/wcms_553635.pdf

260. Bryant-Tokalau, J., 2018: *Indigenous Pacific Approaches to Climate Change: Pacific Island Countries. Palgrave Studies in Disaster Anthropology.* Palgrave Pivot, Cham, Switzerland, 111 pp. https://doi.org/10.1007/978-3-319-78399-4

261. Fletcher, S.M., J. Thiessen, A. Gero, M. Rumsey, N. Kuruppu, and J. Willetts, 2013: Traditional coping strategies and disaster response: Examples from the South Pacific region. *Journal of Environmental and Public Health*, **2013**. https://doi.org/10.1155/2013/264503

262. Granderson, A.A., 2017: The role of traditional knowledge in building adaptive capacity for climate change: Perspectives from Vanuatu. *Weather, Climate, and Society*, **9** (3), 545–561. https://doi.org/10.1175/wcas-d-16-0094.1

263. Nakamura, N. and Y. Kanemasu, 2020: Traditional knowledge, social capital, and community response to a disaster: Resilience of remote communities in Fiji after a severe climatic event. *Regional Environmental Change*, **20** (1), 1–14. https://doi.org/10.1007/s10113-020-01613-w

264. Austin, S.E., R. Biesbroek, L. Berrang-Ford, J.D. Ford, S. Parker, and M.D. Fleury, 2016: Public health adaptation to climate change in OECD countries. *International Journal of Environmental Research and Public Health*, **13** (9), 889. https://doi.org/10.3390/ijerph13090889

265. Dannenberg, A.L., H. Frumkin, J.J. Hess, and K.L. Ebi, 2019: Managed retreat as a strategy for climate change adaptation in small communities: Public health implications. *Climatic Change*, **153** (1), 1–14. https://doi.org/10.1007/s10584-019-02382-0

266. Gero, A., S. Fletcher, M. Rumsey, J. Thiessen, N. Kuruppu, J. Buchan, J. Daly, and J. Willetts, 2015: Disasters and climate change in the Pacific: Adaptive capacity of humanitarian response organizations. *Climate and Development*, **7** (1), 35–46. https://doi.org/10.1080/17565529.2014.899888

267. Kim, R., A. Costello, and D. Campbell-Lendrum, 2015: Climate change and health in Pacific island states. *Bulletin of the World Health Organization*, **93**, 819. https://doi.org/10.2471/blt.15.166199

268. Newnham, E.A., P.L. Dzidic, E.L.P. Mergelsberg, B. Guragain, E.Y.Y. Chan, Y. Kim, J. Leaning, R. Kayano, M. Wright, L. Kaththiriarachchi, H. Kato, T. Osawa, and L. Gibbs, 2020: The Asia Pacific disaster mental health network: Setting a mental health agenda for the region. *International Journal of Environmental Research and Public Health*, **17** (17), 6144. https://doi.org/10.3390/ijerph17176144

269. Anderson, T.R., C.H. Fletcher, M.M. Barbee, B.M. Romine, S. Lemmo, and J.M.S. Delevaux, 2018: Modeling multiple sea level rise stresses reveals up to twice the land at risk compared to strictly passive flooding methods. *Scientific Reports*, **8** (1), 14484. https://doi.org/10.1038/s41598-018-32658-x

270. Habel, S., C.H. Fletcher, T.R. Anderson, and P.R. Thompson, 2020: Sea-level rise induced multi-mechanism flooding and contribution to urban infrastructure failure. *Scientific Reports*, **10** (1), 3796. https://doi.org/10.1038/s41598-020-60762-4

271. Anderson, T.R., C.H. Fletcher, M.M. Barbee, L.N. Frazer, and B.M. Romine, 2015: Doubling of coastal erosion under rising sea level by mid-century in Hawaii. *Natural Hazards*, **78** (1), 75–103. https://doi.org/10.1007/s11069-015-1698-6

272. Quataert, E., C. Storlazzi, A. van Rooijen, O. Cheriton, and A. van Dongeren, 2015: The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines. *Geophysical Research Letters*, **42** (15), 6407–6415. https://doi.org/10.1002/2015gl064861

273. Connell, J. and M. Keen, 2020: Ch. 1. Urbanisation at risk: Urban resilience in Pacific Island countries. In: *Urbanisation at Risk in the Pacific and Asia.* Sanderson, D. and L. Bruce, Eds. Routledge, New York, NY, 3–21. https://doi.org/10.4324/9780429290176

274. Act 016: Relating to Coastal Zone Management. S.B. NO. 2060, S.D. 2, H.D. 2, State of Hawai'i, September 15, 2020. https://www.capitol.hawaii.gov/session2020/bills/gm1121_.pdf

275. Ordinance No. 1088: A Bill for an Ordinance to Amend Chapter 8, Kaua'i County Code 1987, as Amended, Relating to the Comprehensive Zoning Ordinance. Bill No. 2813, Draft 1, State of Hawai'i, County of Kaua'i, January 27, 2021. https://www.kauai.gov/files/assets/public/planning-department/documents/ordinance-no.-1088-bill-no.-2813-draft-1.pdf

276. Ordinance No. 23-3: A Bill for an Ordinance Relating to Shoreline Setbacks. City and County of Honolulu, March 9, 2023. https://hnldoc.ehawaii.gov/hnldoc/document-download?id=16783

277. Ordinance No. 23-4: A Bill for an Ordinance Relating to the Special Management Area. City and County of Honolulu, March 9, 2023. https://hnldoc.ehawaii.gov/hnldoc/document-download?id=16784

278. Maui Planning Commission, 2007: MC-12: Shoreline Rules for the Maui Planning Commission. §12-203. County of Maui, State of Hawaii. https://www.mauicounty.gov/documentcenter/view/8412/chpt-203--mpc-shoreline-procedure-rules?bidid=

279. Maui Planning Commission, 2022: 2022 Updates: Special Management Area and Shoreline Rules. Maui Planning Commission, Maui, HI, 16 pp. https://www.mauicounty.gov/documentcenter/view/133253/frequently-asked-questions---updated-04222022

280. Act 179: Relating to Real Property Transactions. SB. No. 0474, S.D. 1, H.D. 2, C.D. 1, State of Hawai'i, July 2, 2021. https://www.capitol.hawaii.gov/session2021/bills/gm1307_.pdf

281. Act 178: Relating to Sea Level Rise Adaptation. H.B. No. 0243, H.D. 1, S.D. 2, C.D. 1, State of Hawai'i, July 2, 2021. https://www.capitol.hawaii.gov/session2021/bills/gm1306_.pdf

282. Act 015: Relating to Environmental Protection. H.B. No. 2182, H.D. 2, S.D. 2, C.D. 1, State of Hawai'i, June 4, 2018. https://www.capitol.hawaii.gov/sessions/session2018/bills/GM1115_.PDF

283. Hawai'i Office of Planning, 2019: Assessing the Feasibility and Implications of Managed Retreat Strategies for Vulnerable Coastal Areas in Hawai'i. Office of Planning, Coastal Zone Management Program, Honolulu, HI. https://files.hawaii.gov/dbedt/op/czm/ormp/assessing_the_feasibility_and_implications_of_managed_retreat_strategies_for_vulnerable_coastal_areas_in_hawaii.pdf

284. Roelvink, F.E., C.D. Storlazzi, A.R. van Dongeren, and S.G. Pearson, 2021: Coral reef restorations can be optimized to reduce coastal flooding hazards. *Frontiers in Marine Science*, **8**, 653945. https://doi.org/10.3389/fmars.2021.653945

285. Storlazzi, C.D., B.G. Reguero, K.A. Cumming, A.D. Cole, J.B. Shope, Camila Gaido L., T.S. Viehman, B.A. Nickel, and M.W. Beck, 2021: Rigorously Valuing the Potential Coastal Hazard Risk Reduction Provided by Coral Reef Restoration in Florida and Puerto Rico. USGS Open-File Report 2021–1054. U.S. Geological Survey, Reston, VA, 35 pp. https://doi.org/10.3133/ofr20211054

286. Campbell, C., n.d.: Reefense. U.S. Department of Defense, Defense Advanced Research Projects Agency. https://www.darpa.mil/program/reefense

287. Senate Concurrent Resolution: Urging the Department of Land and Natural Resources to Examine and Consider Purchasing Reef Insurance to Support Nature-Based Solutions to Protect Hawaii's Coastlines and Coastal Infrastructure From Natural Disasters. S.C.R. No. 159, S.D. 1, State of Hawai'i, 2021. https://www.capitol.hawaii.gov/sessions/session2021/bills/scr159_sd1_.htm

288. An Act to Establish a Tumon Bay Insurance Task Force to Explore the Feasibility of Obtaining Parametric Insurance for the Reef and Beach of Tumon Bay and to Further Explore a Public-Private Partnership to Effectuate the Same. Bill No. 372-35, Territory of Guam, Pub. L. No. 35-107, October 19, 2020. https://guamlegislature.com/35th_public_laws.htm

289. Ferrario, F., M.W. Beck, C.D. Storlazzi, F. Micheli, C.C. Shepard, and L. Airoldi, 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, **5** (1), 3794. https://doi.org/10.1038/ncomms4794

290. Brander, L. and P. van Beukering, 2013: The Total Economic Value of U.S. Coral Reefs: A Review of the Literature. National Oceanic and Atmospheric Administration, Coral Reef Conservation Program, Silver Spring, MD, 23 pp. https://www.coris.noaa.gov/activities/economic_value/

291. Storlazzi, C.D., B.G. Reguero, A.D. Cole, E. Lowe, J.B. Shope, A.E. Gibbs, B.A. Nickel, R.T. McCall, A.R. van Dongeren, and M.W. Beck, 2019: Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction. USGS Open-File Report 2019–1027. U.S. Geological Survey, Reston, VA, 42 pp. https://doi.org/10.3133/ofr20191027

292. Keen, M. and J. Connell, 2019: Regionalism and resilience? Meeting urban challenges in Pacific island states. *Urban Policy and Research*, **37** (3), 324–337. https://doi.org/10.1080/08111146.2019.1626710

293. Connell, J. and R.P.C. Brown, 2005: Remittances in the Pacific: An Overview. Asian Development Bank, Philippines. https://www.adb.org/sites/default/files/publication/28799/remittances-pacific.pdf

294. The World Bank, 2020: Personal Remittances, Received (% of GDP) - Marshall Islands. World Bank Group. https://data.worldbank.org/indicator/bx.trf.pwkr.dt.gd.zs?locations=mh

295. The World Bank, 2020: Personal Remittances, Received (% of GDP) - Micronesia, Fed. Sts. World Bank Group. https://data.worldbank.org/indicator/bx.trf.pwkr.dt.gd.zs?locations=fm

296. The World Bank, 2020: Personal Remittances, Received (% of GDP) - Palau. World Bank Group. https://data.worldbank.org/indicator/bx.trf.pwkr.dt.gd.zs?locations=pw

297. Campbell, J., 2010: Climate change and population movement in Pacific Island countries. In: *Climate Change and Migration South Pacific Perspectives*. Burson, B., Ed. Institute of Policy Studies, Wellington, New Zealand, 29–50. https://www.researchgate.net/publication/327638277

298. Campbell, J. and O. Warrick, 2014: Climate Change and Migration Issues in the Pacific. United Nations Economic and Social Commission for Asia and the Pacific, Fiji. https://www.ilo.org/dyn/migpractice/docs/261/pacific.pdf

299. van der Geest, K., M. Burkett, J. Fitzpatrick, M. Stege, and B. Wheeler, 2020: Climate change, ecosystem services and migration in the Marshall Islands: Are they related? *Climatic Change*, **161** (1), 109–127. https://doi.org/10.1007/s10584-019-02648-7

300. ADB, 2013: The Economics of Climate Change in the Pacific. Asian Development Bank, Madaluyong City, Philippines. https://www.adb.org/sites/default/files/publication/31136/economics-climate-change-pacific.pdf

301. Fouad, M., N. Novta, G. Preston, T. Schneider, and S. Weerathunga, 2021: Unlocking Access to Climate Finance for Pacific Island Countries. Departmental Paper No. 2021/020. International Monetary Fund, Washington, DC, 103 pp. https://www.imf.org/en/publications/departmental-papers-policy-papers/issues/2021/09/23/unlocking-access-to-climate-finance-for-pacific-islands-countries-464709

302. Bertram, G., 2013: Ch. 27. Pacific Island economies. In: *The Pacific Islands*. Rapaport, M., Ed. University of Hawaii Press, Honolulu, HI, 325–340. https://doi.org/10.1515/9780824865849-029

303. Bertram, I.G. and R.F. Watters, 1986: The MIRAB process: Earlier analyses in context. *Pacific Viewpoint*, **27** (1), 47–59. https://doi.org/10.1111/apv.271003

304. Wolf, F., W.L. Filho, P. Singh, N. Scherle, D. Reiser, J. Telesford, I.B. Miljković, P.H. Havea, C. Li, D. Surroop, and M. Kovaleva, 2021: Influences of climate change on tourism development in small Pacific island states. *Sustainability*, **13** (8), 4223. https://doi.org/10.3390/su13084223

305. The World Bank, 2022: Agriculture, Forestry, and Fishing, Value Added (% of GDP) - Pacific Island Small States. World Bank Group. https://data.worldbank.org/indicator/nv.agr.totl.zs?locations=s2

306. Freestone, D. and D. Cicek, 2021: Legal Dimensions of Sea Level Rise: Pacific Perspective. World Bank Group, Washington, DC. http://hdl.handle.net/10986/35881

307. IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Pachauri, R.K. and L.A. Meyer, Eds. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 151 pp. http://ipcc.ch/report/ar5/syr/

308. Leatherman, S.P., 2018: Coastal erosion and the United States National Flood Insurance Program. *Ocean & Coastal Management*, **156**, 35–42. https://doi.org/10.1016/j.ocecoaman.2017.04.004

309. Kumar, L., S. Jayasinghe, T. Gopalakrishnan, and P.D. Nunn, 2020: Ch. 1. Climate change and the Pacific Islands. In: *Climate Change and Impacts in the Pacific*. Kumar, L., Ed. Springer, Cham, Switzerland, 1–31. https://doi.org/10.1007/978-3-030-32878-8_1

310. USAID, 2021: USAID assists the Federated States of Micronesia and Palau to secure $10.4 million for climate change adaptation. U.S. Agency for International Development, Washington, DC, April 13, 2021. https://www.usaid.gov/news-information/press-releases/apr-13-2021-usaid-assists-federated-states-micronesia-and-palau-climate-change-adaptation

311. ADB, 2018: ADB Support to Boost Palau's Resilience to Natural Disasters. Asian Development Bank. https://www.adb.org/news/adb-support-boost-palaus-resilience-natural-disasters

312. Chapman, A., W. Davies, C. Downey, and D. Dookie, 2021: ADB Climate Risk Country Profile: Micronesia. Asian Development Bank. http://hdl.handle.net/11540/13791

313. ADB, 2022: The Economic Impacts of the End of Compact Grant Assistance in the Freely Associated States. Asian Development Bank. https://pubs.pitiviti.org/adb-fas

314. Zhang, D. and S. Lawson, 2017: China in Pacific regional politics. *The Round Table*, **106** (2), 197–206. https://doi.org/10.1080/00358533.2017.1296705

315. Buhr, B., U. Volz, C. Donovan, G. Kling, Y.C. Lo, V. Murinde, and N. Pullin, 2018: Climate Change and the Cost of Capital in Developing Countries. Imperial College London, SOAS University of London and UN Environment, London and Geneva. https://eprints.soas.ac.uk/26038/

316. Act 97: Relating to Renewable Standards. H.B. NO. 623, State of Hawai'i, 245–247, June 8, 2015. https://www.capitol.hawaii.gov/sessions/session2015/bills/hb623_cd1_.pdf

317. An Act to Amend § 8311 of Article 3, Chapter 8, Title 12, Guam Code Annotated, Relative to Raising the Renewable Portfolio Standards of the Guam Power Authority. Bill No. 80-35, Territory of Guam, Pub. L. No. 35-46, October 31, 2019. https://guamlegislature.com/35th_public_laws.htm

318. Coffman, M., P. Bernstein, M. Schjervheim, S.L. Croix, and S. Hayashida, 2022: Economic and GHG impacts of a US state-level carbon tax: The case of Hawai'i. *Climate Policy*, **22** (7), 935–949. https://doi.org/10.1080/14693062.2022.2061405

319. RMI, 2018: Tile Til Eo—2050 Climate Strategy "Lighting the Way". Republic of the Marshall Islands. https://unfccc.int/documents/182635

320. Republic of Palau, 2022: Palau Reaffirms Commitment to Generating 100% Renewable Energy by 2032 as President Whipps Signs the Moana Pledge Transpacific Agreement. Republic of Palau, Office of the President, Ngerulmud, Palau. https://www.manapacific.com/wp-content/uploads/2022/04/PR22-09-Moana-Pledge_Mana-Pacific.pdf

321. McNamara, K.E., R. Clissold, R. Westoby, A.E. Piggott-McKellar, R. Kumar, T. Clarke, F. Namoumou, F. Areki, E. Joseph, O. Warrick, and P.D. Nunn, 2020: An assessment of community-based adaptation initiatives in the Pacific Islands. *Nature Climate Change*, **10** (7), 628–639. https://doi.org/10.1038/s41558-020-0813-1

322. Nalau, J., S. Becken, and B. Mackey, 2018: Ecosystem-based adaptation: A review of the constraints. *Environmental Science & Policy*, **89**, 357–364. https://doi.org/10.1016/j.envsci.2018.08.014

323. Nunn, P.D., A. Kohler, and R. Kumar, 2017: Identifying and assessing evidence for recent shoreline change attributable to uncommonly rapid sea-level rise in Pohnpei, Federated States of Micronesia, northwest Pacific Ocean. *Journal of Coastal Conservation*, **21** (6), 719–730. https://doi.org/10.1007/s11852-017-0531-7

324. Harvey, C., 2016: This island is now powered almost entirely by solar energy. *The Washington Post*, November 24, 2016. https://www.washingtonpost.com/news/energy-environment/wp/2016/11/24/this-island-is-now-powered-almost-entirely-by-solar-energy/

325. Hawaii State Energy Office, 2020: Hawai'i's Energy Facts and Figures. Hawaii State Energy Office. https://energy.hawaii.gov/wp-content/uploads/2020/11/HSEO_FactsAndFigures-2020.pdf

326. Kaua'i Island Utility Cooperative, 2022: 2021 Annual Renewable Portfolio Standards Status Report. Hawaii Public Utilities Commission, Honolulu, HI. https://dms.puc.hawaii.gov/dms/DocumentViewer?pid=A1001001A22D01A95234F01510

327. Sylvia, T., 2019: Kauai was 100% renewably powered for 32 hours over the last month. *PV Magazine*. https://pv-magazine-usa.com/2019/12/19/in-the-last-month-kauaii-has-been-100-renewably-powered-for-32-hours/

328. Act 100: Relating to Energy. S.B. NO. 1050, S.D.2, H.D.3, C.D.1, State of Hawai'i, June 8, 2015. https://www.capitol.hawaii.gov/sessions/session2015/bills/gm1200_.pdf

329. Teruya, L., 2021: Molokai Has an Electricity Problem. This Co-op Wants to Change That. Honolulu Civil Beat. https://www.civilbeat.org/2021/09/molokai-has-an-electricity-problem-this-co-op-wants-to-change-that/

330. Rubalcaba, J.G., W.C.E.P. Verberk, A.J. Hendriks, B. Saris, and H.A. Woods, 2020: Oxygen limitation may affect the temperature and size dependence of metabolism in aquatic ectotherms. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (50), 31963–31968. https://doi.org/10.1073/pnas.2003292117

331. Lotze, H.K., D.P. Tittensor, A. Bryndum-Buchholz, T.D. Eddy, W.W.L. Cheung, E.D. Galbraith, M. Barange, N. Barrier, D. Bianchi, J.L. Blanchard, L. Bopp, M. Büchner, C.M. Bulman, D.A. Carozza, V. Christensen, M. Coll, J.P. Dunne, E.A. Fulton, S. Jennings, and B. Worm, 2019: Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (26), 12907–12912. https://doi.org/10.1073/pnas.1900194116

332. Hoegh-Guldberg, O., D. Beal, T. Chaudhry, H. Elhaj, A. Abdullat, P. Etessy, and M. Smits, 2015: Reviving the Oceans Economy: The Case for Action—2015. WWF International, Gland, Switzerland, Geneva, 60 pp. https://www.worldwildlife.org/publications/reviving-the-oceans-economy-the-case-for-action-2015

333. Moritz, C., J. Vii, W. Lee Long, J. Tamelander, A. Thomassin, and S. Planes, 2018: Status and Trends of Coral Reefs of the Pacific. Global Coral Reef Monitoring Network. https://www.unep.org/resources/report/status-and-trends-coral-reef-pacific

334. Raymundo, L.J., D. Burdick, W.C. Hoot, R.M. Miller, V. Brown, T. Reynolds, J. Gault, J. Idechong, J. Fifer, and A. Williams, 2019: Successive bleaching events cause mass coral mortality in Guam, Micronesia. *Coral Reefs*, **38** (4), 677–700. https://doi.org/10.1007/s00338-019-01836-2

335. Brainard, R.E., T. Oliver, M.J. McPhaden, A. Cohen, R. Venegas, A. Heenan, B. Vargas-Ángel, R. Rotjan, S. Mangubhai, E. Flint, and S.A. Hunter, 2018: Ecological impacts of the 2015/16 El Niño in the central equatorial Pacific. *Bulletin of the American Meteorological Society*, **99** (1), S21–S26. https://doi.org/10.1175/bams-d-17-0128.1

336. Hughes, T.P., K.D. Anderson, S.R. Connolly, S.F. Heron, J.T. Kerry, J.M. Lough, A.H. Baird, J.K. Baum, M.L. Berumen, T.C. Bridge, D.C. Claar, C.M. Eakin, J.P. Gilmour, N.A.J. Graham, H. Harrison, J.-P.A. Hobbs, A.S. Hoey, M. Hoogenboom, R.J. Lowe, M.T. McCulloch, J.M. Pandolfi, M. Pratchett, V. Schoepf, G. Torda, and S.K. Wilson, 2018: Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, **359** (6371), 80–83. https://doi.org/10.1126/science.aan8048

337. Graham, N.A.J., J.P.W. Robinson, S.E. Smith, R. Govinden, G. Gendron, and S.K. Wilson, 2020: Changing role of coral reef marine reserves in a warming climate. *Nature Communications*, **11** (1), 2000. https://doi.org/10.1038/s41467-020-15863-z

338. McManus, L.C., D.L. Forrest, E.W. Tekwa, D.E. Schindler, M.A. Colton, M.M. Webster, T.E. Essington, S.R. Palumbi, P.J. Mumby, and M.L. Pinsky, 2021: Evolution and connectivity influence the persistence and recovery of coral reefs under climate change in the Caribbean, Southwest Pacific, and Coral Triangle. *Global Change Biology*, **27** (18), 4307–4321. https://doi.org/10.1111/gcb.15725

339. Robinson, J.P.W., S.K. Wilson, S. Jennings, and N.A.J. Graham, 2019: Thermal stress induces persistently altered coral reef fish assemblages. *Global Change Biology*, **25** (8), 2739–2750. https://doi.org/10.1111/gcb.14704

340. Jensen, M.P., C.D. Allen, T. Eguchi, I.P. Bell, E.L. LaCasella, W.A. Hilton, C.A.M. Hof, and P.H. Dutton, 2018: Environmental warming and feminization of one of the largest sea turtle populations in the world. *Current Biology*, **28** (1), 154–159. https://doi.org/10.1016/j.cub.2017.11.057

341. He, Q. and B.R. Silliman, 2019: Climate change, human impacts, and coastal ecosystems in the Anthropocene. *Current Biology*, **29** (19), R1021–R1035. https://doi.org/10.1016/j.cub.2019.08.042

342. Marrack, L., C. Wiggins, J.J. Marra, A. Genz, R. Most, K. Falinski, and E. Conklin, 2021: Assessing the spatial–temporal response of groundwater-fed anchialine ecosystems to sea-level rise for coastal zone management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **31** (4), 853–869. https://doi.org/10.1002/aqc.3493

343. Suárez-Castro, A.F., H.L. Beyer, C.D. Kuempel, S. Linke, P. Borrelli, and O. Hoegh-Guldberg, 2021: Global forest restoration opportunities to foster coral reef conservation. *Global Change Biology*, **27** (20), 5238–5252. https://doi.org/10.1111/gcb.15811

344. Allemand, D. and D. Osborn, 2019: Ocean acidification impacts on coral reefs: From sciences to solutions. *Regional Studies in Marine Science*, **28**, 100558. https://doi.org/10.1016/j.rsma.2019.100558

345. Prouty, N.G., A. Cohen, K.K. Yates, C.D. Storlazzi, P.W. Swarzenski, and D. White, 2017: Vulnerability of coral reefs to bioerosion from land-based source of pollution. *Journal of Geophysical Research Oceans*, **122** (12), 9319–9331. https://doi.org/10.1002/2017jc013264

346. Beyer, H.L., E.V. Kennedy, M. Beger, C.A. Chen, J.E. Cinner, E.S. Darling, C.M. Eakin, R.D. Gates, S.F. Heron, N. Knowlton, D.O. Obura, S.R. Palumbi, H.P. Possingham, M. Puotinen, R.K. Runting, W.J. Skirving, M. Spalding, K.A. Wilson, S. Wood, and O. Hoegh-Guldberg, 2018: Risk-sensitive planning for conserving coral reefs under rapid climate change. *Conservation Letters*, **11** (6), 12587. https://doi.org/10.1111/conl.12587

347. Twilley, R.R., E. Castañeda-Moya, V.H. Rivera-Monroy, and A. Rovai, 2017: Ch. 5. Productivity and carbon dynamics in mangrove wetlands. In: *Mangrove Ecosystems: A Global Biogeographic Perspective*. Rivera-Monroy, V.H., S.Y. Lee, E. Kristensen, and R.R. Twilley, Eds. Springer, Cham, Switzerland, 113–162. https://doi.org/10.1007/978-3-319-62206-4_5

348. Herr, D. and E. Landis, 2016: Coastal Blue Carbon Ecosystems: Opportunities for Nationally Determined Contributions. Policy Brief. International Union for Conservation of Nature and The Nature Conservancy, Gland, Switzerland and Washington, DC. https://www.unep.org/resources/policy-and-strategy/coastal-blue-carbon-ecosystems-opportunities-nationally-determined

349. Hilmi, N., R. Chami, M.D. Sutherland, J.M. Hall-Spencer, L. Lebleu, M.B. Benitez, and L.A. Levin, 2021: The role of blue carbon in climate change mitigation and carbon stock conservation. *Frontiers in Climate*, **3**, 710546. https://doi.org/10.3389/fclim.2021.710546

350. Naylor, R.L., K.M. Bonine, K.C. Ewel, and E. Waguk, 2002: Migration, markets, and mangrove resource use on Kosrae, Federated States of Micronesia. *AMBIO: A Journal of the Human Environment*, **31** (4), 340–350. https://doi.org/10.1579/0044-7447-31.4.340

351. Engilis Jr., A. and M.B. Naughton, 2004: U.S. Pacific Islands Regional Shorebird Conservation Plan. U.S. Shorebird Conservation Plan. U.S. Department of the Interior, Fish and Wildlife Service, Portland, OR. https://www.shorebirdplan.org/wp-content/uploads/2013/01/USPI1.pdf

352. Field, M.E., S.A. Cochran, J.B. Logan, and C.D. Storlazzi, 2008: The Coral Reef of South Moloka'i, Hawai'i—Portrait of a Sediment-Threatened Fringing Reef. Scientific Investigations Report 2007-5101. U.S. Geological Survey. https://pubs.usgs.gov/sir/2007/5101/

353. Soper, F.M., R.A. MacKenzie, S. Sharma, T.G. Cole, C.M. Litton, and J.P. Sparks, 2019: Non-native mangroves support carbon storage, sediment carbon burial, and accretion of coastal ecosystems. *Global Change Biology*, **25** (12), 4315–4326. https://doi.org/10.1111/gcb.14813

354. Jacobi, J.D. and F.R. Warshauer, 2017: Hawaiian Islands Coastal Vegetation Survey 2013-2015. U.S. Geological Survey. https://doi.org/10.5066/f7tt4pvb

355. Saintilan, N., N.S. Khan, E. Ashe, J.J. Kelleway, K. Rogers, C.D. Woodroffe, and B.P. Horton, 2020: Thresholds of mangrove survival under rapid sea level rise. *Science*, **368** (6495), 1118–1121. https://doi.org/10.1126/science.aba2656

356. Reynolds, M.H., K.N. Courtot, P. Berkowitz, C.D. Storlazzi, J. Moore, and E. Flint, 2015: Will the effects of sea-level rise create ecological traps for Pacific Island seabirds? *PLoS ONE*, **10** (9), e0136773. https://doi.org/10.1371/journal.pone.0136773

357. IPCC, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964

358. Blackburn, T.M., P. Cassey, R.P. Duncan, K.L. Evans, and K.J. Gaston, 2004: Avian extinction and mammalian introductions on oceanic islands. *Science*, **305** (5692), 1955–1958. https://doi.org/10.1126/science.1101617

359. Brewington, L., B. Eichelberger, N. Read, E. Parsons, H. Kerkering, C. Martin, W. Miles, J. Idechong, and J. Burgett, 2023: Ch. 5. Pacific Island perspectives on invasive species and climate change. In: *Island Ecosystems: Challenges to Sustainability*. Walsh, S.J., C.F. Mena, J.R. Stewart, and J.P. Muñoz Pérez, Eds. Springer, Cham, Switzerland, 59–78. https://doi.org/10.1007/978-3-031-28089-4_5

360. Fernández-Palacios, J.M., H. Kreft, S.D.H. Irl, S. Norder, C. Ah-Peng, P.A.V. Borges, K.C. Burns, L. de Nascimento, J.-Y. Meyer, E. Montes, and D.R. Drake, 2021: Scientists' warning – The outstanding biodiversity of islands is in peril. *Global Ecology and Conservation*, **31**, e01847. https://doi.org/10.1016/j.gecco.2021.e01847

361. Leclerc, C., F. Courchamp, and C. Bellard, 2018: Insular threat associations within taxa worldwide. *Scientific Reports*, **8** (1), 6393. https://doi.org/10.1038/s41598-018-24733-0

362. Pyšek, P., V. Jarošík, P.E. Hulme, J. Pergl, M. Hejda, U. Schaffner, and M. Vilà, 2012: A global assessment of invasive plant impacts on resident species, communities and ecosystems: The interaction of impact measures, invading species' traits and environment. *Global Change Biology*, **18** (5), 1725–1737. https://doi.org/10.1111/j.1365-2486.2011.02636.x

363. Wilcove, D.S., D. Rothstein, J. Dubow, A. Phillips, and E. Losos, 1998: Quantifying threats to imperiled species in the United States: Assessing the relative importance of habitat destruction, alien species, pollution, overexploitation, and disease. *BioScience*, **48** (8), 607–615. https://doi.org/10.2307/1313420

364. Barbosa, J.M. and G.P. Asner, 2016: Effects of long-term rainfall decline on the structure and functioning of Hawaiian forests. *Environmental Research Letters*, **12** (9), 094002. https://doi.org/10.1088/1748-9326/aa7ee4

365. Madson, A., M. Dimson, L.B. Fortini, K. Kawelo, T. Ticktin, M. Keir, C. Dong, Z. Ma, D.W. Beilman, K. Kay, J.P. Ocón, E. Gallerani, S. Pau, and T.W. Gillespie, 2022: A near four-decade time series shows the Hawaiian Islands have been browning since the 1980s. *Environmental Management*, **71** (5), 965–980. https://doi.org/10.1007/s00267-022-01749-x

366. Banko, P.C., R.J. Camp, C. Farmer, K.W. Brinck, D.L. Leonard, and R.M. Stephens, 2013: Response of palila and other subalpine Hawaiian forest bird species to prolonged drought and habitat degradation by feral ungulates. *Biological Conservation*, **157**, 70–77. https://doi.org/10.1016/j.biocon.2012.07.013

367. Fortini, L., J. Price, J. Jacobi, A. Vorsino, J. Burgett, K. Brinck, S. ʻOhukaniʻohiʻa Gon III, G. Koob, and E. Paxton, 2013: A Landscape-Based Assessment of Climate Change Vulnerability for All Native Hawaiian Plants. Technical Report HCSU-044. University of Hawaiʻi, Hawaiʻi Cooperative Studies Unit, Hilo, HI. https://hilo.hawaii.edu/hcsu/documents/TR44_Fortini_plant_vulnerability_assessment.pdf

368. Barton, K.E., C. Jones, K.F. Edwards, A.B. Shiels, and T. Knight, 2020: Local adaptation constrains drought tolerance in a tropical foundation tree. *Journal of Ecology*, **108** (4), 1540–1552. https://doi.org/10.1111/1365-2745.13354

369. Eldon, J., M.R. Bellinger, and D.K. Price, 2019: Hawaiian picture-winged *Drosophila* exhibit adaptive population divergence along a narrow climatic gradient on Hawaii Island. *Ecology and Evolution*, **9** (5), 2436–2448. https://doi.org/10.1002/ece3.4844

370. Fortini, L.B., P.D. Krushelnycky, D.R. Drake, F. Starr, K. Starr, and C.G. Chimera, 2022: Complex demographic responses to contrasting climate drivers lead to divergent population trends across the range of a threatened alpine plant. *Global Ecology and Conservation*, **33**, 01954. https://doi.org/10.1016/j.gecco.2021.e01954

371. Westerband, A.C., L. Bialic-Murphy, L.A. Weisenberger, and K.E. Barton, 2020: Intraspecific variation in seedling drought tolerance and associated traits in a critically endangered, endemic Hawaiian shrub. *Plant Ecology & Diversity*, **13** (2), 159–174. https://doi.org/10.1080/17550874.2020.1730459

372. Tsang, Y.-P., R.W. Tingley, J. Hsiao, and D.M. Infante, 2019: Identifying high value areas for conservation: Accounting for connections among terrestrial, freshwater, and marine habitats in a tropical island system. *Journal for Nature Conservation*, **50**, 125711. https://doi.org/10.1016/j.jnc.2019.125711

373. Frauendorf, T.C., R.A. MacKenzie, R.W. Tingley III, D.M. Infante, and R.W. El-Sabaawi, 2020: Using a space-for-time substitution approach to predict the effects of climate change on nutrient cycling in tropical island stream ecosystems. *Limnology and Oceanography*, **65** (12), 3114–3127. https://doi.org/10.1002/lno.11577

374. Gagne, R.B. and M.J. Blum, 2016: Parasitism of a native Hawaiian stream fish by an introduced nematode increases with declining precipitation across a natural rainfall gradient. *Ecology of Freshwater Fish*, **25** (3), 476–486. https://doi.org/10.1111/eff.12228

375. Tingley III, R.W. 2017: Conserving Streams With Changing Climate: A Multi-Scaled Research Framework to Consider Current and Future Condition of Hawaiian Stream Habitats. Doctor of Philosophy in Fisheries and Wildlife, Michigan State University, 181 pp. https://d.lib.msu.edu/etd/4575

376. Trauernicht, C., 2019: Vegetation—rainfall interactions reveal how climate variability and climate change alter spatial patterns of wildland fire probability on Big Island, Hawaii. *Science of The Total Environment*, **650**, 459–469. https://doi.org/10.1016/j.scitotenv.2018.08.347

377. Nugent, A.D., R.J. Longman, C. Trauernicht, M.P. Lucas, H.F. Diaz, and T.W. Giambelluca, 2020: Fire and rain: The legacy of Hurricane Lane in Hawai'i. *Bulletin of the American Meteorological Society*, **101** (6), 954–967. https://doi.org/10.1175/bams-d-19-0104.1

378. Trauernicht, C., E. Pickett, C.P. Giardina, C.M. Litton, S. Cordell, and A. Beavers, 2015: The contemporary scale and context of wildfire in Hawai'i. *Pacific Science*, **69** (4), 427–444. https://doi.org/10.2984/69.4.1

379. Aslan, C.E., C.T. Liang, A.B. Shiels, and W. Haines, 2018: Absence of native flower visitors for the endangered Hawaiian mint *Stenogyne angustifolia*: Impending ecological extinction? *Global Ecology and Conservation*, **16**, e00468. https://doi.org/10.1016/j.gecco.2018.e00468

380. Fortini, L.B., C.R. Leopold, K.S. Perkins, O.A. Chadwick, S.G. Yelenik, J.D. Jacobi, K. Bishaw, and M. Gregg, 2021: Landscape level effects of invasive plants and animals on water infiltration through Hawaiian tropical forests. *Biological Invasions*, **23** (7), 2155–2172. https://doi.org/10.1007/s10530-021-02494-8

381. Ibanez, T. and P.J. Hart, 2020: Spatial patterns of tree recruitment in a montane Hawaiian wet forest after cattle removal and pig population control. *Applied Vegetation Science*, **23** (2), 197–209. https://doi.org/10.1111/avsc.12478

382. Strauch, A.M., G.L. Bruland, R.A. MacKenzie, and C.P. Giardina, 2016: Soil and hydrological responses to wild pig (*Sus scofa*) exclusion from native and strawberry guava (*Psidium cattleianum*)-invaded tropical montane wet forests. *Geoderma*, **279**, 53–60. https://doi.org/10.1016/j.geoderma.2016.05.021

383. Yeung, N.W. and K.A. Hayes, 2018: Biodiversity and extinction of Hawaiian land snails: How many are left now and what must we do to conserve them—A reply to Solem (1990). *Integrative and Comparative Biology*, **58** (6), 1157–1169. https://doi.org/10.1093/icb/icy043

384. Ainsworth, A. and D.R. Drake, 2020: Classifying Hawaiian plant species along a habitat generalist-specialist continuum: Implications for species conservation under climate change. *PLoS ONE*, **15** (2), 0228573. https://doi.org/10.1371/journal.pone.0228573

385. Louppe, V., B. Leroy, A. Herrel, and G. Veron, 2020: The globally invasive small Indian mongoose *Urva auropunctata* is likely to spread with climate change. *Scientific Reports*, **10** (1), 7461. https://doi.org/10.1038/s41598-020-64502-6

386. Sommer, R.M. and R.H. Cowie, 2020: Invasive traits of veronicellid slugs in the Hawaiian Islands and temperature response suggesting possible range shifts under a changing climate. *Journal of Molluscan Studies*, **86** (2), 147–155. https://doi.org/10.1093/mollus/eyz042

387. Veazey, L., O. Williams, R. Wade, R. Toonen, and H.L. Spalding, 2019: Present-day distribution and potential spread of the invasive green alga *Avrainvillea amadelpha* around the main Hawaiian Islands. *Frontiers in Marine Science*, **6**, 402. https://doi.org/10.3389/fmars.2019.00402

388. Dudley, B.D., R.F. Hughes, G.P. Asner, J.A. Baldwin, Y. Miyazawa, H. Dulai, C. Waters, J. Bishop, N.R. Vaughn, J. Yeh, S. Kettwich, R.A. MacKenzie, R. Ostertag, and T. Giambelluca, 2020: Hydrological effects of tree invasion on a dry coastal Hawaiian ecosystem. *Forest Ecology and Management*, **458**, 117653. https://doi.org/10.1016/j.foreco.2019.117653

389. Michaud, J., S. Cordell, T.C. Cole, and R. Ostertag, 2015: Drought in an invaded Hawaiian lowland wet forest. *Pacific Science*, **69** (3), 367–383. https://doi.org/10.2984/69.3.6

390. Takahashi, M., T.W. Giambelluca, R.G. Mudd, J.K. DeLay, M.A. Nullet, and G.P. Asner, 2011: Rainfall partitioning and cloud water interception in native forest and invaded forest in Hawai'i Volcanoes National Park. *Hydrological Processes*, **25** (3), 448–464. https://doi.org/10.1002/hyp.7797

391. van Kleunen, M., W. Dawson, F. Essl, J. Pergl, M. Winter, E. Weber, H. Kreft, P. Weigelt, J. Kartesz, M. Nishino, L.A. Antonova, J.F. Barcelona, F.J. Cabezas, D. Cárdenas, J. Cárdenas-Toro, N. Castaño, E. Chacón, C. Chatelain, A.L. Ebel, E. Figueiredo, N. Fuentes, Q.J. Groom, L. Henderson, Inderjit, A. Kupriyanov, S. Masciadri, J. Meerman, O. Morozova, D. Moser, D.L. Nickrent, A. Patzelt, P.B. Pelser, M.P. Baptiste, M. Poopath, M. Schulze, H. Seebens, W.-s. Shu, J. Thomas, M. Velayos, J.J. Wieringa, and P. Pyšek, 2015: Global exchange and accumulation of non-native plants. *Nature*, **525** (7567), 100–103. https://doi.org/10.1038/nature14910

392. Beaury, E.M., J.T. Finn, J.D. Corbin, V. Barr, and B.A. Bradley, 2020: Biotic resistance to invasion is ubiquitous across ecosystems of the United States. *Ecology Letters*, **23** (3), 476–482. https://doi.org/10.1111/ele.13446

393. U.S. Department of the Navy, 2015: Regional Biosecurity Plan for Micronesia and Hawaii. Volume I. University of Guam and the Secretariat of the Pacific Community. https://www.doi.gov/sites/doi.gov/files/uploads/pac_regional_biosecurity_plan_for_micronesia_and_hawaii_volume_i.pdf

394. Finch, D.M., J.L. Butler, J.B. Runyon, C.J. Fettig, F.F. Kilkenny, S. Jose, S.J. Frankel, S.A. Cushman, R.C. Cobb, J.S. Dukes, J.A. Hicke, and S.K. Amelon, 2021: Ch. 4. Effects of climate change on invasive species. In: *Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector*. Poland, T.M., T. Patel-Weynand, D.M. Finch, C.F. Miniat, D.C. Hayes, and V.M. Lopez, Eds. Springer, Cham, Switzerland, 57–83. https://doi.org/10.1007/978-3-030-45367-1_4

395. Hellmann, J.J., J.E. Byers, B.G. Bierwagen, and J.S. Dukes, 2008: Five potential consequences of climate change for invasive species. *Conservation Biology*, **22** (3), 534–543. https://doi.org/10.1111/j.1523-1739.2008.00951.x

396. Lockwood, J.L., M.F. Hoopes, and M.P. Marchetti, 2013: *Invasion Ecology*. Wiley-Blackwell, 456 pp. https://www.wiley.com/en-ie/invasion+ecology,+2nd+edition-p-9781444333640

397. Balzotti, C.S., G.P. Asner, E.D. Adkins, and E.W. Parsons, 2020: Spatial drivers of composition and connectivity across endangered tropical dry forests. *Journal of Applied Ecology*, **57** (8), 1593–1604. https://doi.org/10.1111/1365-2664.13632

398. Barbosa, J.M. and G.P. Asner, 2017: Prioritizing landscapes for restoration based on spatial patterns of ecosystem controls and plant–plant interactions. *Journal of Applied Ecology*, **54** (5), 1459–1468. https://doi.org/10.1111/1365-2664.12857

399. Camp, R.J., R. Loh, S.P. Berkowitz, K.W. Brinck, J.D. Jacobi, J. Price, S. McDaniel, and L.B. Fortini, 2018: Potential Impacts of Projected Climate Change on Vegetation Management in Hawai`i Volcanoes National Park. U.S. Department of the Interior, National Park Service, 10 pp. https://pubs.er.usgs.gov/publication/70196506

400. Fortini, L.B. and J.D. Jacobi, 2018: Identifying opportunities for long-lasting habitat conservation and restoration in Hawaii's shifting climate. *Regional Environmental Change*, **18** (8), 2391–2402. https://doi.org/10.1007/s10113-018-1342-6

401. Wada, C.A., L.L. Bremer, K. Burnett, C. Trauernicht, T. Giambelluca, L. Mandle, E. Parsons, C. Weil, N. Kurashima, and T. Ticktin, 2017: Estimating cost-effectiveness of Hawaiian dry forest restoration using spatial changes in water yield and landscape flammability under climate change. *Pacific Science*, **71** (4), 401–424. https://doi.org/10.2984/71.4.2

402. von Holle, B., S. Yelenik, and E.S. Gornish, 2020: Restoration at the landscape scale as a means of mitigation and adaptation to climate change. *Current Landscape Ecology Reports*, **5** (3), 85–97. https://doi.org/10.1007/s40823-020-00056-7

403. Bremer, L.L., C.A. Wada, S. Medoff, J. Page, K. Falinski, and K.M. Burnett, 2019: Contributions of native forest protection to local water supplies in East Maui. *Science of The Total Environment*, **688**, 1422–1432. https://doi.org/10.1016/j.scitotenv.2019.06.220

404. Burnett, K.M., T. Ticktin, L.L. Bremer, S.A. Quazi, C. Geslani, C.A. Wada, N. Kurashima, L. Mandle, P.a. Pascua, T. Depraetere, D. Wolkis, M. Edmonds, T. Giambelluca, K. Falinski, and K.B. Winter, 2019: Restoring to the future: Environmental, cultural, and management trade-offs in historical versus hybrid restoration of a highly modified ecosystem. *Conservation Letters*, **12** (1), e12606. https://doi.org/10.1111/conl.12606

405. Bremer, L.L., L. Mandle, C. Trauernicht, P.a. Pascua, H.L. McMillen, K. Burnett, C.A. Wada, N. Kurashima, S.A. Quazi, T. Giambelluca, P. Chock, and T. Ticktin, 2018: Bringing multiple values to the table: Assessing future land-use and climate change in North Kona, Hawai'i. *Ecology and Society*, **23** (1), 33. https://doi.org/10.5751/es-09936-230133

406. CRHI, 2021: Nature-Based Resilience and Adaptation to Climate Change in Hawai'i. Climate Ready Hawai'i. https://climate.hawaii.gov/wp-content/uploads/2021/04/CRHI-Working-Paper-V5.pdf

407. Richmond, R.H., Y. Golbuu, and A.J. Shelton III, 2019: Ch. 26. Successful management of coral reef-watershed networks. In: *Coasts and Estuaries*. Wolanski, E., J.W. Day, M. Elliott, and R. Ramachandran, Eds. Elsevier, 445–459. https://doi.org/10.1016/b978-0-12-814003-1.00026-5

408. Friedlander, A.M. and C.F. Gaymer, 2021: Progress, opportunities and challenges for marine conservation in the Pacific Islands. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **31** (2), 221–231. https://doi.org/10.1002/aqc.3464

409. Loope, L.L., R.F. Hughes, and J.-Y. Meyer, 2013: Ch. 15. Plant invasions in protected areas of tropical Pacific islands, with special reference to Hawaii. In: *Plant Invasions in Protected Areas: Patterns, Problems and Challenges*. Foxcroft, L.C., P. Pyšek, D.M. Richardson, and P. Genovesi, Eds. Springer, Dordrecht, Netherlands, 313–348. https://doi.org/10.1007/978-94-007-7750-7_15

410. Gaüzère, P., F. Jiguet, and V. Devictor, 2016: Can protected areas mitigate the impacts of climate change on bird's species and communities? *Diversity and Distributions*, **22** (6), 625–637. https://doi.org/10.1111/ddi.12426

411. Lawler, J.J. and J. Hepinstall-Cymerman, 2010: Ch. 15. Conservation planning in a changing climate: Assessing the impacts of potential range shifts on a reserve network. In: *Landscape-Scale Conservation Planning*. Trombulak, S.C. and R.F. Baldwin, Eds. Springer, Dordrecht, Netherlands, 325–348. https://doi.org/10.1007/978-90-481-9575-6_15

412. Roberts, C.M., B.C. O'Leary, D.J. McCauley, P.M. Cury, C.M. Duarte, J. Lubchenco, D. Pauly, A. Sáenz-Arroyo, U.R. Sumaila, R.W. Wilson, B. Worm, and J.C. Castilla, 2017: Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (24), 6167–6175. https://doi.org/10.1073/pnas.1701262114

413. Virkkala, R., J. Pöyry, R.K. Heikkinen, A. Lehikoinen, and J. Valkama, 2014: Protected areas alleviate climate change effects on northern bird species of conservation concern. *Ecology and Evolution*, **4** (15), 2991–3003. https://doi.org/10.1002/ece3.1162

414. Judge, S.W., C.C. Warren, R.J. Camp, L.K. Berthold, H.L. Mounce, P.J. Hart, and R.J. Monello, 2021: Population estimates and trends of three Maui Island-endemic Hawaiian honeycreepers. *Journal of Field Ornithology*, **92** (2), 115–126. https://doi.org/10.1111/jofo.12364

415. Paxton, E.H., R.J. Camp, P.M. Gorresen, L.H. Crampton, D.L. Leonard, and E.A. VanderWerf, 2016: Collapsing avian community on a Hawaiian island. *Science Advances*, **2** (9), e1600029. https://doi.org/10.1126/sciadv.1600029

416. Liao, W., C.T. Atkinson, D.A. LaPointe, and M.D. Samuel, 2017: Mitigating future avian malaria threats to Hawaiian forest birds from climate change. *PLoS ONE*, **12** (1), e0168880. https://doi.org/10.1371/journal.pone.0168880

417. Paxton, E.H., M. Laut, S. Enomoto, and M. Bogardus, 2022: Hawaiian Forest Bird Conservation Strategies for Minimizing the Risk of Extinction: Biological and Biocultural Considerations. Hawaii Cooperative Studies Unit Technical Report 103. University of Hawai'i at Hilo, Hawai'i Cooperative Studies Unit, 119 pp. https://pubs.er.usgs.gov/publication/70230509

418. Paxton, E.H., M. Laut, J.P. Vetter, and S.J. Kendall, 2018: Research and management priorities for Hawaiian forest birds. *The Condor*, **120** (3), 557–565. https://doi.org/10.1650/condor-18-25.1

419. Samuel, M.D., W. Liao, C.T. Atkinson, and D.A. LaPointe, 2020: Facilitated adaptation for conservation – Can gene editing save Hawaii's endangered birds from climate driven avian malaria? *Biological Conservation*, **241**, 108390. https://doi.org/10.1016/j.biocon.2019.108390

420. Fortini, L.B., L.R. Kaiser, and D.A. LaPointe, 2020: Fostering real-time climate adaptation: Analyzing past, current, and forecast temperature to understand the dynamic risk to Hawaiian honeycreepers from avian malaria. *Global Ecology and Conservation*, **23**, 01069. https://doi.org/10.1016/j.gecco.2020.e01069

421. Fantle-Lepczyk, J., L. Crampton, A. Taylor, D. Duffy, and S. Conant, 2020: An analysis of translocation regimes for the endangered puaiohi *Myadestes palmeri*. *Endangered Species Research*, **41**, 105–118. https://doi.org/10.3354/esr01011

422. Fortini, L.B., L.R. Kaiser, A.E. Vorsino, E.H. Paxton, and J.D. Jacobi, 2017: Assessing the potential of translocating vulnerable forest birds by searching for novel and enduring climatic ranges. *Ecology and Evolution*, **7** (21), 9119–9130. https://doi.org/10.1002/ece3.3451

423. Rivera, S.N., L.B. Fortini, S. Plentovich, and M.R. Price, 2021: Perceived barriers to the use of assisted colonization for climate sensitive species in the Hawaiian Islands. *Environmental Management*, **68** (3), 329–339. https://doi.org/10.1007/s00267-021-01491-w

424. van Dooren, T., 2019: Moving birds in Hawai'i: Assisted colonisation in a colonised land. *Cultural Studies Review*, **25** (1), 41–64. https://doi.org/10.5130/csr.v25i1.6392

425. Kueffer, C. and K. Kinney, 2017: What is the importance of islands to environmental conservation? *Environmental Conservation*, **44** (4), 311–322. https://doi.org/10.1017/s0376892917000479

426. McMillen, H., T. Ticktin, and H.K. Springer, 2017: The future is behind us: Traditional ecological knowledge and resilience over time on Hawai'i Island. *Regional Environmental Change*, **17** (2), 579–592. https://doi.org/10.1007/s10113-016-1032-1

427. Winter, K.B., K. Beamer, M.B. Vaughan, A.M. Friedlander, M.H. Kido, A.N. Whitehead, M.K.H. Akutagawa, N. Kurashima, M.P. Lucas, and B. Nyberg, 2018: The moku system: Managing biocultural resources for abundance within social-ecological regions in Hawai'i. *Sustainability*, **10** (10), 3554. https://doi.org/10.3390/su10103554

428. Winter, K.B., T. Ticktin, and S.A. Quazi, 2020: Biocultural restoration in Hawai'i also achieves core conservation goals. *Ecology and Society*, **25** (1). https://doi.org/10.5751/es-11388-250126

429. Keali'ikanaka'oleohaililani, K., N. Kurashima, K.S. Francisco, C.P. Giardina, R.P. Louis, H. McMillen, C.K. Asing, K. Asing, T.A. Block, M. Browning, K. Camara, L. Camara, M.L. Dudley, M. Frazier, N. Gomes, A.E. Gordon, M. Gordon, L. Heu, A. Irvine, N. Kaawa, S. Kirkpatrick, E. Leucht, C.H. Perry, J. Replogle, L.-L. Salbosa, A. Sato, L. Schubert, A. Sterling, A.L. Uowolo, J. Uowolo, B. Walker, A.N. Whitehead, and D. Yogi, 2018: Ritual + sustainability science? A portal into the science of Aloha. *Sustainability*, **10** (10), 3478. https://doi.org/10.3390/su10103478

430. Diver, S., M. Vaughan, M. Baker-Médard, and H. Lukacs, 2019: Recognizing "reciprocal relations" to restore community access to land and water. *International Journal of the Commons*, **13** (1), 400–429. https://doi.org/10.18352/ijc.881

431. Vaughan, M.B. and P.M. Vitousek, 2013: Mahele: Sustaining communities through small-scale inshore fishery catch and sharing networks. *Pacific Science*, **67** (3), 329–344. https://doi.org/10.2984/67.3.3

432. Kamelamela, K.L., H.K. Springer, R. Ku'ulei Keakealani, M.U. Ching, T. Ticktin, R.D. Ohara, E.W. Parsons, E.D. Adkins, K.S. Francisco, and C. Giardina, 2022: Kōkua aku, Kōkua mai: An Indigenous consensus-driven and place-based approach to community led dryland restoration and stewardship. *Forest Ecology and Management*, **506**, 119949. https://doi.org/10.1016/j.foreco.2021.119949

433. Morishige, K., P. Andrade, P. Pascua, K. Steward, E. Cadiz, L. Kapono, and U. Chong, 2018: Nā Kilo 'Āina: Visions of biocultural restoration through Indigenous relationships between people and place. *Sustainability*, **10** (10), 3368. https://doi.org/10.3390/su10103368

434. Harmon, K.C., K.B. Winter, N. Kurashima, C.H. Fletcher, H.H. Kane, and M.R. Price, 2021: The role of indigenous practices in expanding waterbird habitat in the face of rising seas. *Anthropocene*, **34**, 100293. https://doi.org/10.1016/j.ancene.2021.100293

435. Andrade, P. and K. Morishige, 2022: Huli'a: Every place has a story … Let's listen. *Parks Stewardship Forum*, **38** (2). https://doi.org/10.5070/p538257525

436. Andrade, P., K. Morishige, A. Mau, L. Kapono, and E.C. Franklin, 2022: Re-imagining contemporary conservation to support 'Āina Momona: Productive and thriving communities of people, place, and natural resources. *Parks Stewardship Forum*, **38** (2). https://doi.org/10.5070/p538257511

437. Kane, H.H., C.H. Fletcher, E.E. Cochrane, J.X. Mitrovica, S. Habel, and M. Barbee, 2017: Coastal plain stratigraphy records tectonic, environmental, and human habitability changes related to sea-level drawdown, 'Upolu, Sāmoa. *Quaternary Research*, **87** (2), 246–257. https://doi.org/10.1017/qua.2017.2

438. Kayanne, H., T. Yasukochi, T. Yamaguchi, H. Yamano, and M. Yoneda, 2011: Rapid settlement of Majuro Atoll, central Pacific, following its emergence at 2000 years CalBP. *Geophysical Research Letters*, **38** (20). https://doi.org/10.1029/2011gl049163

439. Morgan, W.N., 1988: *Prehistoric Architecture in Micronesia*. University of Texas Press, New York, USA. https://doi.org/10.7560/765061

440. Pukui, M.K., 1983: *'Ōlelo No'eau: Hawaiian Proverbs and Poetical Sayings*. Bishop Museum Press, 372 pp. https://bishopmuseumpress.org/products/olelo-no-eau-hawaiian-proverbs-poetical-sayings-1

441. Hui Mālama Loko I'a, 2020: Loko I'a Needs Assessment. University of Hawai'i, Sea Grant College Program and Pacific Islands Climate Adaptation Science Center. https://seagrant.soest.hawaii.edu/loko-i%CA%BBa-needs-assessment/

442. Kurashima, N., L. Fortini, and T. Ticktin, 2019: The potential of Indigenous agricultural food production under climate change in Hawai'i. *Nature Sustainability*, **2** (3), 191–199. https://doi.org/10.1038/s41893-019-0226-1

443. Pascua, P., H. McMillen, T. Ticktin, M. Vaughan, and K.B. Winter, 2017: Beyond services: A process and framework to incorporate cultural, genealogical, place-based, and Indigenous relationships in ecosystem service assessments. *Ecosystem Services*, **26**, 465–475. https://doi.org/10.1016/j.ecoser.2017.03.012

444. Office of Hawaiian Affairs, National Oceanic and Atmospheric Administration, U.S. Fish and Wildlife Service, and State of Hawai'i, 2021: Mai Ka Pō Mai: A Native Hawaiian Guidance Document for Papahānaumokuākea Marine National Monument. Office of Hawaiian Affairs, Honolulu, HI. https://www.papahanaumokuakea.gov/new-heritage/maikapomai/

445. Trauernicht, C., T. Ticktin, H. Fraiola, Z. Hastings, and A. Tsuneyoshi, 2018: Active restoration enhances recovery of a Hawaiian mesic forest after fire. *Forest Ecology and Management*, **411**, 1–11. https://doi.org/10.1016/j.foreco.2018.01.005

446. MacLeod, L., 2021: More than personal communication: Templates for citing Indigenous elders and knowledge keepers. *KULA: Knowledge Creation, Dissemination, and Preservation Studies*, **5** (1). https://doi.org/10.18357/kula.135

447. Carroll, S.R., E. Herczog, M. Hudson, K. Russell, and S. Stall, 2021: Operationalizing the CARE and FAIR Principles for Indigenous Data Futures. *Scientific Data*, **8** (1), 108. https://doi.org/10.1038/s41597-021-00892-0

448. Hudson, M., N.A. Garrison, R. Sterling, N.R. Caron, K. Fox, J. Yracheta, J. Anderson, P. Wilcox, L. Arbour, A. Brown, M. Taualii, T. Kukutai, R. Haring, B. Te Aika, G.S. Baynam, P.K. Dearden, D. Chagné, R.S. Malhi, I. Garba, N. Tiffin, D. Bolnick, M. Stott, A.K. Rolleston, L.L. Ballantyne, R. Lovett, D. David-Chavez, A. Martinez, A. Sporle, M. Walter, J. Reading, and S.R. Carroll, 2020: Rights, interests and expectations: Indigenous perspectives on unrestricted access to genomic data. *Nature Reviews Genetics*, **21** (6), 377–384. https://doi.org/10.1038/s41576-020-0228-x

449. Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, **93** (4), 485–498. https://doi.org/10.1175/bams-d-11-00094.1

450. Eyring, V., S. Bony, G.A. Meehl, C.A. Senior, B. Stevens, R.J. Stouffer, and K.E. Taylor, 2016: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, **9** (5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

451. Strauch, A.M., R.A. MacKenzie, C.P. Giardina, and G.L. Bruland, 2015: Climate driven changes to rainfall and streamflow patterns in a model tropical island hydrological system. *Journal of Hydrology*, **523**, 160–169. https://doi.org/10.1016/j.jhydrol.2015.01.045

452. Bell, J. and T. Bahri, 2018: A new climate change vulnerability assessment for fisheries and aquaculture. *SPC Fisheries Newsletter*, **156**, 43–56. https://www.conservation.org/docs/default-source/publication-pdfs/a-new-climate-change-vulnerability-assessment-for-fisheries-and-aquaculture.pdf?status=master&sfvrsn=d209baa7_2

453. Savage, A., H. Bambrick, and D. Gallegos, 2020: From garden to store: Local perspectives of changing food and nutrition security in a Pacific Island country. *Food Security*, **12** (6), 1331–1348. https://doi.org/10.1007/s12571-020-01053-8

454. Bird, Z., V. Iese, H.J. Des Combes, M. Wairiu, and L.B.K. Yuen, 2022: Assessing the impacts of climate change on domestic crop production: Experience and perception of local farmers in North Malaita, Solomon Islands. *Journal of Interdisciplinary Research*, **6** (1), 77–98. https://doi.org/10.26021/12507

455. Xue, L., Y. Wang, A.J. Newman, K. Ikeda, R.M. Rasmussen, T.W. Giambelluca, R.J. Longman, A.J. Monaghan, M.P. Clark, and J.R. Arnold, 2020: How will rainfall change over Hawai'i in the future? High-resolution regional climate simulation of the Hawaiian Islands. *Bulletin of Atmospheric Science and Technology*, **1** (3), 459–490. https://doi.org/10.1007/s42865-020-00022-5

456. Bailey, R.T., J.W. Jenson, D. Rubinstein, and A.E. Olsen, 2008: Groundwater Resources of Atoll Islands: Observations, Modeling, and Management. Technical Report No. 119. University of Guam, Water and Environmental Research Institute of the Western Pacific. https://weri-cdn.uog.edu/wp-content/PDFs/TRs/WERI%20TR%20119%20-%20Bailey%20et%20al%202008.pdf

457. Gingerich, S.B., 2013: The Effects of Withdrawals and Drought on Groundwater Availability in the Northern Guam Lens Aquifer, Guam. USGS Scientific Investigations Report 2013-5216. U.S. Geological Survey, 76 pp. https://doi.org/10.3133/sir20135216

458. Izuka, S.K., K. Rotzoll, and T. Nishikawa, 2021: Volcanic Aquifers of Hawai'i—Construction and Calibration of Numerical Models for Assessing Groundwater Availability on Kaua'i, O'ahu, and Maui. USGS Scientific Investigations Report 2020-5126. U.S. Geological Survey, 63 pp. https://doi.org/10.3133/sir20205126

459. USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp. https://doi.org/10.7930/j0r49nqx

460. Cinner, J.E. and M.L. Barnes, 2019: Social dimensions of resilience in social-ecological systems. *One Earth*, **1** (1), 51–56. https://doi.org/10.1016/j.oneear.2019.08.003

461. Cohen, M.C.L., R.J. Lara, E. Cuevas, E.M. Oliveras, and L. Da Silveira Sternberg, 2016: Effects of sea-level rise and climatic changes on mangroves from southwestern littoral of Puerto Rico during the middle and late Holocene. CATENA, **143**, 187–200. https://doi.org/10.1016/j.catena.2016.03.041

462. Nunn, P.D., R. McLean, A. Dean, T. Fong, V. Iese, M. Katonivualiku, C. Klöck, I. Korovulavula, R. Kumar, and T. Tabe, 2020: Ch. 14. Adaptation to climate change: Contemporary challenges and perspectives. In: *Climate Change and Impacts in the Pacific*. Kumar, L., Ed. Springer, Cham, Switzerland, 499–524. https://doi.org/10.1007/978-3-030-32878-8_14

463. Warrick, O., W. Aalbersberg, P. Dumaru, R. McNaught, and K. Teperman, 2017: The 'Pacific Adaptive Capacity Analysis Framework': Guiding the assessment of adaptive capacity in Pacific Island communities. *Regional Environmental Change*, **17** (4), 1039–1051. https://doi.org/10.1007/s10113-016-1036-x

464. Moser, S.C., 2019: The adaptive mind: Psychosocial support for professionals working on the frontlines of climate change. In: *AGU Fall Meeting Abstracts*. American Geophysical Union. https://ui.adsabs.harvard.edu/abs/2019agufm.u13b..06m/abstract

465. Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas, 2017: Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 75 pp. https://repository.library.noaa.gov/view/noaa/18399

466. Bertana, A., 2020: The role of power in community participation: Relocation as climate change adaptation in Fiji. *Environment and Planning C: Politics and Space*, **38** (5), 902–919. https://doi.org/10.1177/2399654420909394

467. Donner, S.D. and S. Webber, 2014: Obstacles to climate change adaptation decisions: A case study of sea-level rise and coastal protection measures in Kiribati. *Sustainability Science*, **9** (3), 331–345. https://doi.org/10.1007/s11625-014-0242-z

468. Hermann, E. and W. Kempf, 2017: Climate change and the imagining of migration: Emerging discourses on Kiribati's land purchase in Fiji. *The Contemporary Pacific*, **29** (2), 231–263. http://hdl.handle.net/10125/58115

469. McMichael, C., 2020: Human mobility, climate change, and health: Unpacking the connections. *The Lancet Planetary Health*, **4** (6), e217–e218. https://doi.org/10.1016/s2542-5196(20)30125-x

470. Piggott-McKellar, A.E., K.E. McNamara, P.D. Nunn, and S.T. Sekinini, 2019: Moving people in a changing climate: Lessons from two case studies in Fiji. *Social Sciences*, **8** (5), 133. https://doi.org/10.3390/socsci8050133

471. Tabe, T., 2019: Climate change migration and displacement: Learning from past relocations in the Pacific. *Social Sciences*, **8** (7), 218. https://doi.org/10.3390/socsci8070218

472. Rubinstein, D.H. and M.J. Levin, 1992: Micronesian migration to Guam: Social and economic characteristics. *Asian and Pacific Migration Journal*, **1** (2), 350–385. https://doi.org/10.1177/011719689200100208

473. Paudel, S., S. Mansfield, L.F. Villamizar, T.A. Jackson, and S.D.G. Marshall, 2021: Can biological control overcome the threat from newly invasive coconut rhinoceros beetle populations (*Coleoptera: Scarabaeidae*)? A review. *Annals of the Entomological Society of America*, **114** (2), 247–256. https://doi.org/10.1093/aesa/saaa057

474. Caasi, J.A.S., A.L. Guerrero, K. Yoon, L.J.C. Aquino, A. Moore, H. Oh, J. Rychtář, and D. Taylor, 2023: A mathematical model of invasion and control of coconut rhinoceros beetle *Oryctes rhinoceros* (L.) in Guam. *Journal of Theoretical Biology*, **570**, 111525. https://doi.org/10.1016/j.jtbi.2023.111525

475. Marshall, S.D.G., A. Moore, M. Vaqalo, A. Noble, and T.A. Jackson, 2017: A new haplotype of the coconut rhinoceros beetle, *Oryctes rhinoceros*, has escaped biological control by *Oryctes rhinoceros* nudivirus and is invading Pacific Islands. *Journal of Invertebrate Pathology*, **149**, 127–134. https://doi.org/10.1016/j.jip.2017.07.006

476. Soto, I., R.N. Cuthbert, A. Kouba, C. Capinha, A. Turbelin, E.J. Hudgins, C. Diagne, F. Courchamp, and P.J. Haubrock, 2022: Global economic costs of herpetofauna invasions. *Scientific Reports*, **12** (1), 10829. https://doi.org/10.1038/s41598-022-15079-9

477. Fritts, T.H., 2002: Economic costs of electrical system instability and power outages caused by snakes on the Island of Guam. *International Biodeterioration & Biodegradation*, **49** (2), 93–100. https://doi.org/10.1016/S0964-8305(01)00108-1

478. Chu, E.K. and C.E.B. Cannon, 2021: Equity, inclusion, and justice as criteria for decision-making on climate adaptation in cities. *Current Opinion in Environmental Sustainability*, **51**, 85–94. https://doi.org/10.1016/j.cosust.2021.02.009

479. Doswald, N., R. Munroe, D. Roe, A. Giuliani, I. Castelli, J. Stephens, I. Möller, T. Spencer, B. Vira, and H. Reid, 2014: Effectiveness of ecosystem-based approaches for adaptation: Review of the evidence-base. *Climate and Development*, **6** (2), 185–201. https://doi.org/10.1080/17565529.2013.867247

480. Sudmeier-Rieux, K., T. Arce-Mojica, H.J. Boehmer, N. Doswald, L. Emerton, D.A. Friess, S. Galvin, M. Hagenlocher, H. James, P. Laban, C. Lacambra, W. Lange, B.G. McAdoo, C. Moos, J. Mysiak, L. Narvaez, U. Nehren, P. Peduzzi, F.G. Renaud, S. Sandholz, L. Schreyers, Z. Sebesvari, T. Tom, A. Triyanti, P. van Eijk, M. van Staveren, M. Vicarelli, and Y. Walz, 2021: Scientific evidence for ecosystem-based disaster risk reduction. *Nature Sustainability*, **4** (9), 803–810. https://doi.org/10.1038/s41893-021-00732-4

481. Oppenheimer, M., B.C. Glavovic, J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari, 2019: Ch. 4. Sea level rise and implications for low-lying islands, coasts and communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 321–445. https://doi.org/10.1017/9781009157964.006

482. Renaud, F.G., K. Sudmeier-Rieux, M. Estrella, and U. Nehren, Eds., 2016: *Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice*. Springer, Cham, Switzerland, 598 pp. https://doi.org/10.1007/978-3-319-43633-3

483. Sasmito, S.D., D. Murdiyarso, D.A. Friess, and S. Kurnianto, 2016: Can mangroves keep pace with contemporary sea level rise? A global data review. *Wetlands Ecology and Management*, **24** (2), 263–278. https://doi.org/10.1007/s11273-015-9466-7

484. Zeng, Y., D.A. Friess, T.V. Sarira, K. Siman, and L.P. Koh, 2021: Global potential and limits of mangrove blue carbon for climate change mitigation. *Current Biology*, **31** (8), 1737–1743. https://doi.org/10.1016/j.cub.2021.01.070

485. Atkinson, C.T., R.B. Utzurrum, D.A. Lapointe, R.J. Camp, L.H. Crampton, J.T. Foster, and T.W. Giambelluca, 2014: Changing climate and the altitudinal range of avian malaria in the Hawaiian Islands – An ongoing conservation crisis on the island of Kaua'i. *Global Change Biology*, **20** (8), 2426–2436. https://doi.org/10.1111/gcb.12535

486. Samuel, M.D., P.H.F. Hobbelen, F. DeCastro, J.A. Ahumada, D.A. LaPointe, C.T. Atkinson, B.L. Woodworth, P.J. Hart, and D.C. Duffy, 2011: The dynamics, transmission, and population impacts of avian malaria in native Hawaiian birds: A modeling approach. *Ecological Applications*, **21** (8), 2960–2973. https://doi.org/10.1890/10-1311.1

Fifth National Climate Assessment: Chapter 31

# Adaptation

# Chapter 31. Adaptation

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# Introduction

Changes in the climate have been observed and experienced across every region of the United States (Ch. 3). Chronic changes such as increasing temperatures, sea level rise, and changing precipitation patterns are affecting the frequency and intensity of diverse extreme weather events. These changes directly impact many millions of people and ecosystems (Ch. 2)[1] and are projected to increase in the future. Adaptation is essential for human and ecological survival in this rapidly changing, complex, and interconnected world.

Adaptation refers to actions taken to reduce risks from today's changed climate conditions and to prepare for further impacts in the future. It includes diverse activities designed to reduce climate-related risks and increase capacity to prepare for climate impacts (Table 31.1). Actions taken to adapt to climate change often provide major opportunities to create a healthier and more resilient future for generations to come. Through these actions, billions of dollars can be saved by investing now and avoiding future losses, new jobs can be created, innovative solutions can be realized, and productivity and efficiencies can be increased across all sectors. Done well, adaptation can protect human lives, improve quality of life, enhance social equity, reduce healthcare costs, and safeguard and restore the natural ecosystems on which society depends for its very survival.

The various risks driven by climate change are extensive, diverse, and intensifying, and they interact with complex social, geographic, economic, and political contexts to exacerbate underlying stresses in overburdened and frontline communities. These communities already experience disproportionate impacts of climate change, and these impacts will only increase over time if equitable adaptation actions are not taken now (KM 31.2). The loss of biodiversity and ecosystem services, the displacement of people due to rising sea levels and more frequent extreme weather events, the loss of natural resources, the increased demand on the aging energy grid and critical infrastructure, and many other challenges will only get worse if society does not transform the way it tackles climate change in the US today.

The urgency for climate adaptation is clear and very well documented.[1,2,3,4,5] The benefits of climate adaptation can be immense and felt by everyone if advanced and scaled sufficiently in relation to the pace of climate change (KM 31.1), if equity is centered from the start (KM 31.2), and if both transformative and incremental adaptation actions are taken now (KM 31.3). Transformative adaptation aims to reduce risks through fundamental shifts in systems, values, and practices. Equitable adaptation intentionally incorporates recognitional, procedural, contextual, and distributional principles of equity in design, planning, and execution. Equitable adaptation addresses the disproportionate effects of climate change for overburdened and frontline communities. It dismantles barriers, considers underlying stresses, creates opportunities, and enables learning through iterative evaluation and sustained engagement.[6]

Effective adaptation governance needs to empower all voices to navigate (e.g., discuss, weigh, and prioritize) competing goals in a collaborative manner (KM 31.4), and adaptation-related services need to go beyond the traditional offerings of science, data, and information to be more accessible and to meet the needs of overburdened and frontline communities (KM 31.5). Adaptation finance and investments will be needed to scale, support, and implement adaptation, and systems will need to be developed to adequately track and evaluate the effectiveness of these investments (KM 31.6). In brief, widespread and dedicated adaptation efforts will be essential for securing a sustainable and prosperous future for all.

**Table 31.1. Example Climate-Related Adaptation Actions**

This table provides examples of incremental and transformative actions being implemented at various scales across US regions and sectors and by various actors to adapt to a range of different climate hazards. See cross-references to other chapters for more detail on certain adaptation actions. The "action" categories in this table have been adapted from Biagini et al. 2014, Hicke et al. 2022, and GCC 2022.[1,7,8]

| Action | Description |
|---|---|
| **Capacity Building** | Community building (KM 23.5); interdisciplinary public education, literacy, and outreach at all age levels; trainings (KM 21.4) and workshops; knowledge and skill development; technical assistance; dissemination of decision-useful information; equitable partnerships (KM 24.5); sharing best and leading practices; local groups and coalitions to assist communities (KM 25.5) |
| **Early Warning and Observing Systems** | Developing, testing, and deploying monitoring and observing systems; early warning systems (e.g., for heat, famine, drought, wildfire); strategic foresight; upgrading weather or hydrometeorological services |
| **Financing** | Insurance (KM 21.5); microfinance; funding; investments; grants; contingency funds; environmental impact bonds (KM 21.4); land trusts (KM 21.5); equitable availability and accessibility of capital before and after disasters (KM 31.6); community-based public–private partnership (KM 24.4) |
| **Physical Infrastructure** | Coastal accommodation; ecosystem-based adaptation; minimizing ecosystem stressors; restoration or creation of natural areas (KMs 23.5, 31.4); revegetation; afforestation woodland management; increased landscape cover; natural coastal embankments; floodable parks and parking structures; flood mitigation (Box 22.1; KM 24.4); urban flood management (KM 31.4); stormwater management (KM 21.4); retention and detention ponds; "living" roofs; rain gardens; green space (KM 21.3); building or retrofitting infrastructure to withstand future climate change (KM 31.5); water capture and storage; water supply and distribution; infrastructure for health services; improvements to water and sanitation infrastructure; adaptive buildings; reservoirs for water storage; irrigation systems (KM 31.3); canal infrastructure; seawalls; solar infrastructure for electrification; restoration of native species diversity; increase in structural diversity (e.g., variation in age structure; KM 24.2); air conditioners (KM 21.1); cooling centers (KM 31.2); sustainable development (KM 23.5) |
| **Information** | Decision support tools (KM 21.1); data analytics; public reporting and disclosures; visualization tools; data acquisition efforts; digital databases; remote communication technologies; climate hazard, vulnerability, and probabilistic mapping tools (KM 21.1); collaboration and coproduction of data and information (KM 24.2); toolkits (KMs 21.1, 31.5) |
| **Management and Planning** | Scenario-based planning (KM 25.5); spatial planning; incorporating climate change and adaptation into planning (e.g., hazard mitigation plans), design standards, management, and decisions (KM 21.1); collaborative adaptation planning at multiple scales (e.g., federal, regional, state, territorial, Tribal, local, organizational [public and private]); assessing underlying conditions and needs (KM 21.4), risks (KM 23.5), adaptive capacity, and options; adaptive management; cooperative governance (KM 31.4); cultural adaptation; regional collaboratives (KM 31.4) |
| **Policy** | Law and governance (KMs 21.3, 23.5); local climate policy (KMs 21.3, 23.5, 27.1); revised design parameters, adaptive building codes, and integration of future climate projections into codes and standards (KMs 12.3, 31.5); creation of new policies or revisions of policies or regulations to allow flexibility to adapt; mainstreaming adaptation into development policies; improvement of water resource governance |
| **Practice and Behavior** | Institutional change; changes to diets and food waste; diversification of livelihoods and income sources; adaptive farm, fishery, or livestock practices (Box 29.5); improved crop varieties; food storage, distribution, and security; disaster risk reduction; permanent migration, planned retreat, or relocation (KMs 21.3, 24.4); seasonal or temporary mobility; social safety nets and cohesion; adaptive social protection; water use and demand; soil or land management techniques; post-harvest storage; rainwater collection; expanding integrated pest management; strategic coastal retreat (KM 9.3); land protection; changes in transportation habits; improved public health (KM 23.5) |
| **Technology** | Developing new or expanding existing technologies to enable and advance adaptation; water use or water access improvement technologies; solar energy capacity; wind power; energy storage; biogas; water purification; solar salt production; microgrids; artificial intelligence and machine learning |

## Key Message 31.1

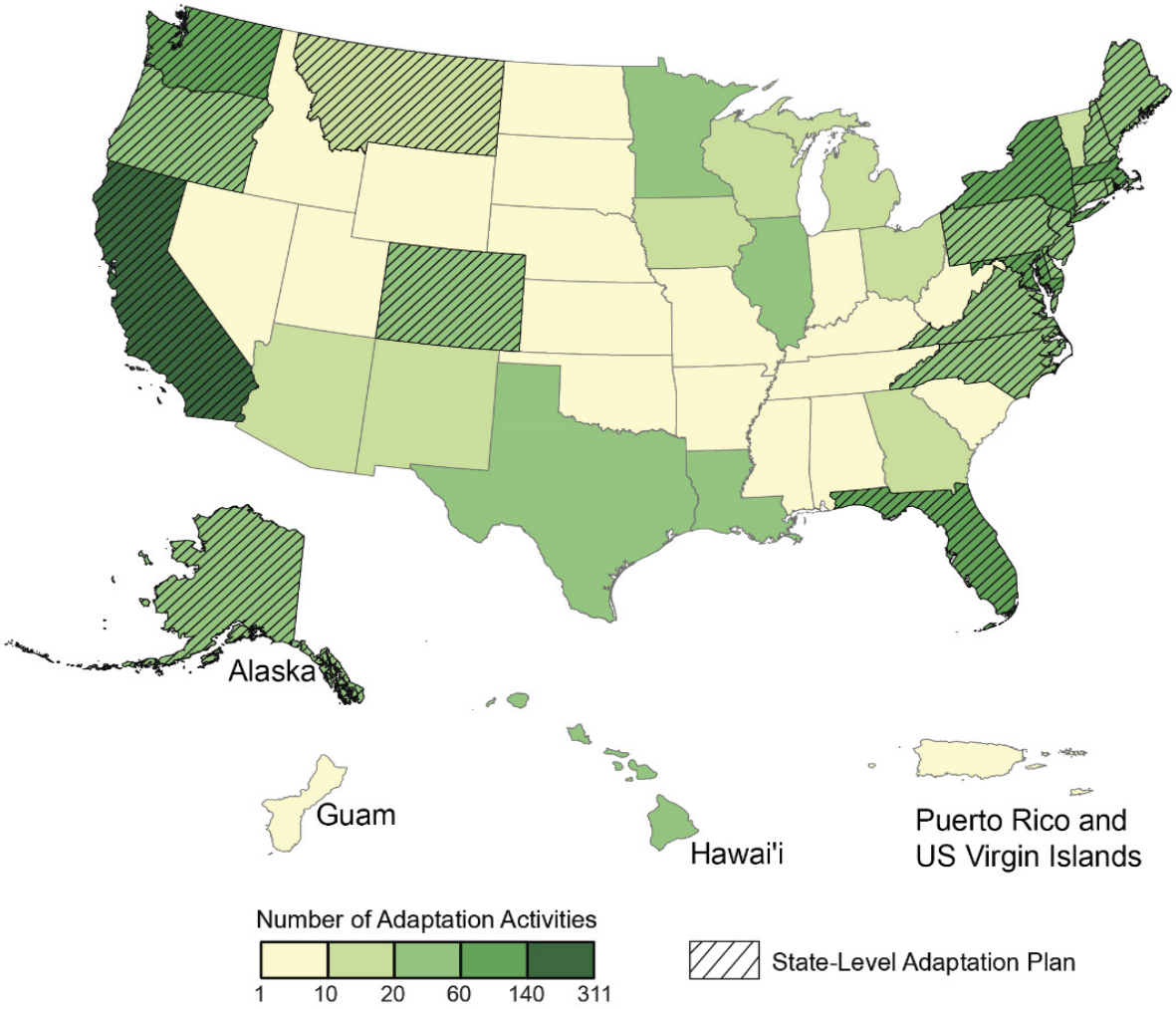
# Adaptation Is Occurring but Is Insufficient in Relation to the Pace of Climate Change

Diverse adaptation activities are occurring across the US (*very high confidence*). Adaptation activities are increasingly moving from awareness and assessment toward planning and implementation (*medium confidence*), with limited advancement toward monitoring and evaluation (*high confidence*). Numerous social, economic, physical, and psychological barriers are preventing more widespread adoption and implementation of adaptation (*high confidence*). Current adaptation efforts and investments are insufficient to reduce today's climate-related risks (*high confidence*) and are unlikely to keep pace with future changes in the climate (*medium confidence*).

Actors, stakeholders, and rights-holders (hereafter actors)—from individuals and organizations to companies, communities, and government entities across all levels, regions, and sectors—are already investing in adaptation measures (Figure 31.1) to reduce the harms caused by climate change and leverage new opportunities to enhance their ability (or capacity) to adapt.[9,10,11,12,13,14] The extent, type, and stage (Box 31.1) of these activities vary regionally and across sectors (Figure 31.1; Chs. 4–16, 21–30). Adaptation has increasingly progressed from the awareness and assessment stages toward planning and implementation (Box 31.1). However, few adaptation activities advance monitoring or evaluation.

To date, adaptation across the US has been incremental in nature, and given the expected future pace of climate change, more action is needed at greater rates and larger scales, across more sectors, and in context-specific ways.[1,15,16,17,18] Historically, actions to adapt often have not centered equity (KM 31.2) and were not designed using a systems-oriented, regional, or collaborative approach for transformation (KM 31.3). Adaptation lacks the attention, investment, financing, and monitoring needed to prepare for both acute and chronic climate impacts (KM 31.6).

## Number of Publicly Documented Adaptation Activities (2018–2022)




**The level of documented public- and private-sector adaptation activity varies widely across US states and territories.**

**Figure 31.1.** This figure illustrates the number of public- and private-sector adaptation activities—see examples offered in Table 31.1—publicly documented and/or updated since 2018. There are several states that have publicly documented numerous adaptation activities, while others have very few or have not documented the activities. Figure credit: WSP, University of Delaware, and University of California, Irvine. See figure metadata for additional contributors.

## Box 31.1. Evidence of Adaptation Occurring Across the Five Adaptation Stages

Adaptation actions are generally categorized into five stages, from raising awareness to implementation and evaluation.[4,19] Evidence of action exists along the five adaptation stages at varying scales and levels.

### Stage 1: Awareness and Engagement

American adults understand that climate change is happening (72%).[20] However, they have low risk awareness (e.g., they underappreciate how severely climate change might affect themselves and society) and lack a clear understanding of adaptation and its importance (KM 31.2).

### Stage 2: Assessment

Approximately 40% of US states have assessed their climate change risks.[8] Of US-based companies disclosing through CDP (formerly the Carbon Disclosure Project), 88% have assessed their climate-related financial risks in alignment with the Task Force on Climate-related Financial Disclosures (KM 31.6)[21] and, if material, disclosed such risks in their financial statements. Assessments of adaptive capacity (the potential of a system to adjust to climate change) and climate resilience have progressed but lag assessments of climate risks, raising concerns that some actors, including local governments, may be ill-equipped to prepare for climate change. There is an increase in the number of publicly available datasets and tools to inform assessments, as well as use of Traditional Knowledge and climate storytelling.

### Stage 3: Policy and Planning

Many governments and organizations have individual sustainability, resilience, or adaptation plans (Figure 31.1). Eighteen states have climate adaptation plans, and another six states have plans underway. Thirty-two states lack a public adaptation plan, a select few US-based companies have disclosed adaptation-related actions they are taking, and very few jurisdictions have adaptation plans co-designed between the private- and public-sectors. Across jurisdictions, plans are developed for different reasons (e.g., climate impacts, investor requests, regulatory requirements) and rarely in a coordinated, collaborative, or regional manner.[22,23] As required in Executive Orders 14008 and 14057, more than 20 federal agencies have prepared and updated climate adaptation plans.[24] Funding and implementation of adaptation plans remains moderate or low (KM 31.6).[1,25] Climate adaptation–related congressional legislation is becoming more prevalent, but it is often embedded within other topics (e.g., infrastructure, disaster relief, water). Federally funded opportunities remain untapped and inaccessible to overburdened and frontline communities.[26]

### Stage 4: Implementation

Implementation of adaptation actions has made some progress. However, most actions have been incremental in nature; have focused on acute extreme weather events rather than systemic, chronic climate change; and/or involve small infrastructure changes to business-as-usual activity, such as changing irrigation systems or expanding stormwater pipes to withstand increased flooding.[1,15] Current levels and types of adaptation being implemented are insufficient to deal with future climate change.[1,15,27,28]

### Stage 5: Monitoring and Evaluation

Adaptation researchers and practitioners are starting to track the number of actions, assess the adaptation effectiveness of those that have occurred, and evaluate the long-term sufficiency of adaptation projects. However, frameworks, monitoring, indicators, and evaluations that assess adaptation practices, co-benefits, equality, and implementation at appropriate levels of granularity are still under development.[1,29,30,31,32,33,34,35] Research is focused on evaluating adaptation-enabling governance structures and barriers to adaptation.[36,37]

## Evidence of Adaptation Barriers

Although adaptation is occurring across the US, barriers remain. These barriers can mostly be overcome with financial, cultural, technological, legislative, or institutional changes.[38,39]

There is growing divergence in the ways government, private industry, and civil society are planning for climate adaptation, with each focusing on a subset of climate vulnerability—disaster resilience, risk and liability, and equity and justice, respectively[40]—and individual climate hazards (e.g., sea level rise, flooding, heat), instead of compounding and complex events (Focus on Compound Events). This incoherence increases the potential for investments that may unintentionally exacerbate climate-related risks or overlook the need to target adaptations for frontline communities that experience a plethora of compounding issues (both chronic and acute), creating greater societal vulnerability to climate impacts (KM 31.3).[41] It is also important to distinguish between *planning* for adaptation and *actually* adapting; there is still more of the former than the latter. The ability to adapt is uneven and inequitable: communities or businesses with means, wealth, or access to resources are more able to adapt, while those with fewer means or opportunities are less able to adapt. The gap between planning and action could also be due to the ease of tracking adaptation plans compared to tracking evidence of systems, people, or environments that are adapting, which can take years to show progress.[1] With the lack of consistent tracking and evaluation of adaptive capacity and how effectively society and ecosystems are adapting to climate change, it is challenging to measure progress, continually improve, and understand the overall impact of adaptation actions and investments.[42]

Adaptation is routinely limited by a range of political, structural, psychological, and normative barriers.[1] Few regulatory requirements focus directly on adaptation.[26] Existing environmental and disaster policies, frameworks, and governance systems are ill-suited to handle the long-term, widespread, transformative changes needed to adapt to climate change; tend to be reactive rather than proactive; and assume fixed rather than dynamic environments.[43,44,45]

Methodologies and tools to assess climate risks, adaptive capacity, and adaptation options are lacking in transparency or are nascent (KM 31.5). While there are many datasets and tools to inform adaptation, their usefulness for decision-making remains uncertain.[46] Resources remain constrained and dispersed when it comes to assessing climate change and adaptation.[43,44,47,48] There is a lack of clear pathways for sharing datasets and tools among multiple actors and jurisdictions (KM 31.4) and a lack of streamlined and transparent processes for integrating local and Traditional Knowledge. The inherent time lag in the scientific peer-review process of science and assessments does not allow for progress to be made swiftly.

Competing values and goals held by diverse public entities and organizations and differentiated responsibilities across levels of government or types of organizations create challenges in developing shared goals (KM 31.4).[44,45,48] The lack of coordination across government agencies at all scales and with diverse actors creates a fragmented and ineffective adaptation governance system.[47,48,49,50,51] The continued reliance on fossil fuel economies discourages transition and economic diversification,[52,53,54] limiting collaborative planning with these high-emitting industries.

Justice and equity are rarely centered in adaptation activities by all sectors and actors (public and private; KM 31.2).[55] In many settings, there is not a widely accessible forum for local participation, particularly of Indigenous communities living in remote and vulnerable locations. Social hierarchies and structures can prevent overburdened groups from sharing their opinions, preventing achieving equitable adaptation. Frontline communities are hit first and worst by climate change, and oftentimes adapting to climate change may not be their immediate concern. Intentionally centering equity in adaptation solutions in partnership with frontline communities has the potential to improve some systemic issues such as inequality, discrimination, and limited access to essential resources and opportunities (KM 31.2).[56]

Finally, there remains a minimal degree of investment and funding for adaptation. As for the funding that is available, communities with the highest climate vulnerability do not have adequate and equitable access to these funds (KM 31.6).[43] Organizations often do not understand potential returns on investment in adaptation, so there is less appetite for expensive measures (KM 31.6).[57]

## Key Message 31.2

## Effective Adaptation Requires Centering Equity

People and communities are affected by climate change in different ways (*very high confidence*). How people and institutions adapt depends on social factors, including individual and community preferences, capacity, and access to resources (*very high confidence*). Adaptation processes, decisions (about whether, where, and how adaptation occurs), and actions that do not explicitly address the uneven distribution of climate harms, and the social processes and injustices underlying these disparities, can exacerbate social inequities and increase exposure to climate harms (*high confidence*).

Climate adaptation that responds to people's values, concerns, and priorities requires not only identifying disparities in how people are affected by climate change but also understanding the underlying causes and conditions of climate vulnerability. Vulnerability (predisposition to adverse impacts) is shaped by interactions across physical, social, and ecological processes (Chs. 3, 20).[58] The places most vulnerable to climate change share traits of high *exposure* to climate change and climate hazards (e.g., long-term water scarcity and extreme drought), high *susceptibility* to adverse impacts, and constraints on *capacity* to adapt.[1] The specific mechanisms that produce vulnerability vary from place to place and over time; are shaped by historical racial, ethnic, gender, and socioeconomic inequalities (Chs. 16, 20);[59] and are sensitive to climatic and demographic change in the future.[60]

Inequalities in social, economic, and political power and resources[61] mean that populations marginalized by society and underserved by government or private-sector systems often face disproportionately worse effects of hazards. For example, higher proportions of Native American, Hispanic, Asian and Pacific Islander, and African American populations live in places prone to extreme wildfire, heat, floods, and permafrost thaw.[62,63,64,65,66,67] Such differential exposure often results from historical injustices such as housing discrimination, forced displacement, social exclusion, lack of investment in hazard mitigation, and lack of provision of other social services by government or the private sector (e.g., insurance, mortgage lending).

Uneven patterns of climate hazard exposure are well documented. Recent work is helping to untangle context-specific processes through which the geographic distribution of climate hazards and social inequality interact to shape local experiences of vulnerability (Ch. 20). Examples include illuminating how disaster damage exacerbates long-term wealth inequality,[68] how disaster assistance distribution policies and differential access constrain recovery outcomes,[69,70] and the influence of racial and economic privilege in flood buyout programs.[71,72,73] Greater understanding of the complex human drivers of climate vulnerability can illustrate how and why transformative adaptations may be required (see KM 31.3) to address interlocking social processes and to remedy vulnerability at its roots (Ch. 20).[40] This improved understanding reinforces why effective adaptation extends beyond cost efficiency and technocratic concerns to intentionally incorporate equity and environmental justice principles.[18,74] Effective adaptation that centers equity is needed to address disparities in the causes and effects of climate risks, dismantle barriers, and create opportunities for all people to thrive.

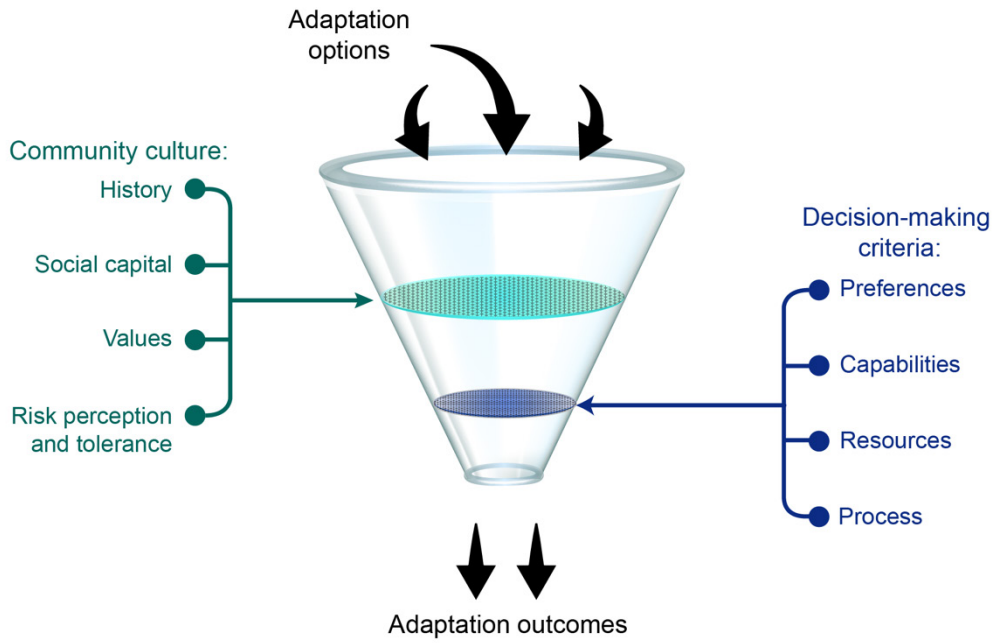
Whether, when, and how people adapt to climate change depends on complex geographic, political, economic, social, and cultural contexts (Chs. 18, 20; Figure 31.2). The ability of individuals and institutions to engage in adaptation is affected by their access to resources, which is unevenly distributed and mediated by factors such as income, race, ethnicity, and gender.[72,75,76,77,78] Factors such as citizenship status and land ownership can create administrative hurdles.[79,80] Federal or state resources for adaptation are often available to individuals, communities, and Tribes only if they navigate bureaucratic systems or succeed in competitions. Equity concerns arise when the system privileges those who already have resources—time, English-language skills, personnel, power, and/or funds to acquire adaptation resources.[68,81,82] Rural or less populous towns, for example, may have fewer professionals to dedicate time to grant applications, fewer resources to meet federal cost-share requirements, or difficulty in proving that adaptation would be cost effective (Ch. 11; KMs 11.3, 31.6). Private-sector adaptation resources are similarly more available to some people than others, as when insurance companies cease to offer wildfire insurance in some risk-prone areas.[83]

Social factors—including place attachment, identity, social capital, and perceptions of what is fair and effective—influence the adaptation actions people are willing and able to pursue.[84,85,86,87] Risk perceptions and risk tolerances are influenced by social factors such as experience, culture, and demographics, and increased risk awareness alone does not predict increased adaptation.[88,89] For example, a survey of Puerto Rican farmers found that half did not engage in adaptation even though they perceived themselves to be at risk and to be capable of taking action.[89] A survey of homeowners in North Carolina found that knowledge of climate change and its risks had no effect on the adaptation actions taken.[88]

Geographic, political, economic, social, and cultural contexts also influence how people adapt (Figure 31.2). Different types of adaptation actions reduce risk to different degrees and in different ways, cost different amounts, have different downsides, and benefit and harm different groups.[90,91,92] Individual and community values, circumstances, and priorities shape which benefits are considered most important, which trade-offs people are willing to endure, and what opportunities they are willing to forego. For example, building seawalls can disconnect communities from the water, which may affect their place attachment, recreational and economic amenities, sense of identity, local ecosystems, and long-term risk profile, while providing short-term gains in safety and property values.[93,94] Culture, heritage, and traditional ties to the land influence adaptation preferences[95,96] and can be important sources of motivation and guidance, especially for locally led adaptation efforts.[97] People may disagree about the goals of adaptation and their preferences for trade-offs, values, or risk tolerance levels, and how these disagreements are handled within a community or institution further shapes adaptation practices.

Participatory processes create space for people to discuss goals, values, social factors, and resources and are a necessary element of participatory justice, which holds that those affected by decisions should be involved in the decision-making process. Such processes benefit from practices that facilitate participation, such as convenient meeting times, language translation, and provision of transportation, food, and childcare. To more deeply embed equity, participatory processes designed to stunt power imbalances—such as those featuring transparency, information access, and opportunities for substantive influence—are most likely to represent the full range of people affected by a decision.

## Adaptation Actions Defined by Multiple Factors




**Adaptation outcomes are the result of individual and group values and decision-making processes and constraints.**

**Figure 31.2.** The path from potential adaptation options to adaptation outcomes is filtered through culture and decision-making criteria, processes, and resources. Individual traits, circumstances, and preferences mean that adaptation outcomes are not identical for all members of a community. These social factors may create, perpetuate, or exacerbate existing social inequities in a systemic fashion, such that even passive actions can produce inequitable outcomes. Intentionally integrating equity into adaptation, which requires accounting for differences in access, capacity, and resources, can lead to more inclusive and sustainable outcomes. Figure credit: ICF, University of Delaware, and University of Iowa.

Failure to intentionally center equity—as in the distribution of resources, participatory processes, and recognition of local contexts—may unintentionally increase the vulnerability of people and places.[98] This is a type of maladaptation, in which efforts to address a climate vulnerability unintentionally increases vulnerability.[99,100] Maladaptation can occur, for example, if engineered infrastructure (e.g., levees) or disaster response programs create a false sense of security that incentivizes continued development in hazardous areas, which in turn produces higher losses in the event of system failure—a situation known as the safe development paradox.[101,102,103] Adaptation tailored to a specific context can become maladaptive if subjected to a different hazard type or context, as when crowded spaces in community shelters or cooling centers contribute to the spread of a pandemic.[104,105] Interventions advanced in the name of engineering adaptation may undermine ecological adaptation, and adaptation for some people (e.g., wealthy communities, homeowners) may lead to maladaptive outcomes for others (e.g., low- to moderate-income communities, renters). Given the potential for maladaptation to substantially redistribute or amplify risk, the topic would benefit from significant attention from practitioners and policymakers.[106,107,108]

Intentionally centering equity in the design, planning, and implementation stages of adaptation would require a paradigm shift. This shift would include asking a number of questions: For whom, with whom, and by whom would proposed adaptation actions be undertaken? Who would benefit and who would be burdened by these actions? Are steps being taken to lessen the burdens borne by underserved populations (Ch. 20; Figure 20.1)?[109,110] This type of proactive engagement from disadvantaged and frontline communities

would be especially important in transformative adaptations that may cause substantial social upheaval (KM 31.3). Accounting for intersecting identities and structural inequalities as organizing principles of adaptation planning could help produce adaptation actions that simultaneously mitigate the effects of climate change and address compounding social inequities.[111,112] Other strategies for equity-centric adaptation include prioritizing adaptation actions and assessing adaptation effectiveness based on satisfying the needs and preferences of the most vulnerable.[113] Adaptation equity and environmental justice involve multiple concepts, including recognition of how past injustices have contributed to current patterns of exposure and capacity, consideration of cultural values and norms, fair decision-making processes and distribution of resources, and efforts to redress past and current injustices.[95,108,114,115,116] Adaptation efforts that center equity and justice are best positioned to avoid perpetuating social injustices.[40,113,117]

The Justice40 Initiative[118] is an example of public policy that centers the redress of social inequity in adaptation. Justice40 defines investment focus areas of climate change, energy, health, transit, affordable housing, pollution reduction, water infrastructure, and workforce development. It calls for 40% of benefits from federal investments in these areas to occur in communities disadvantaged by historical marginalization, pollution hazards, and long-standing underinvestment. To identify disadvantaged communities, the White House Council on Environmental Quality developed an online geospatial application called the Climate and Economic Justice Screening Tool (CEJST). CEJST is primarily designed to be used by federal agencies[119] and could significantly shape the distribution of adaptation resources by the Department of Energy, Department of Housing and Urban Affairs (HUD), Federal Emergency Management Agency (FEMA), and other agencies. CEJST can also inform adaptation investment decisions by business and philanthropic organizations and raise public awareness of the social factors that shape climate vulnerability and adaptation.

## Key Message 31.3

## Transformative Adaptation Will Be Needed to Adequately Address Climate-Related Risks

Climate adaptation actions undertaken in the United States to date have generally been small in scale and incremental in approach, involving minor changes to business as usual (*very high confidence*). Transformative adaptation, which involves more fundamental shifts in systems, values, and practices, will be necessary in many cases to adequately address the risks of current and future climate change (*high confidence*). New monitoring and evaluation methods will also be needed to assess the effectiveness and sufficiency of adaptation and to address equity (*high confidence*).

Most adaptation efforts across a wide range of sectors across the United States have involved incremental adaptation: minor shifts in usual practices that affect small geographic areas and that have been limited in their ability to affect multiple sectors or hazards by technical, social, and economic barriers.[1,15,27,120] Although the performance of adaptation actions is difficult to assess, the available evidence suggests that many US adaptation practices are not sufficient to deal with either current or future climate change.[27,121] Future adaptation may require not only more adaptation efforts (more actions, scaled up, across a wider range of actors, sectors, and systems) but also more transformative adaptation: actions that involve persistent, novel, in-depth changes that shift the fundamental traits of institutions, behaviors, values, or technologies across multiple scales and sectors.[90,122,123] Transformative adaptation can involve changes to the built environment,

or it may involve fundamental changes in economic and governance paradigms to redress historical injustices and center equity and justice.[40]

Adaptation actions in the US more often involve using air-conditioning during heatwaves, increasing irrigation or temporarily reducing water consumption to address frequent droughts, using sandbags to resist coastal erosion, redefining fisheries boundaries in response to shifting habitats, or elevating homes above flood waters—rather than more transformative actions such as redesigning cities and buildings to address heat, shifting water-intensive industry to match new rainfall patterns, or directing new housing development to less flood-prone areas.[1,15,27,120,124] A range of cognitive biases sometimes make people favor incremental change, such as status quo bias (an inclination to preserve the current state even if changes would bring greater benefits).[73,125] However, preserving the status quo can perpetuate existing systems of inequality (KM 31.2).[116,126] Incremental adaptation has also been favored in part due to the framing of adaptation as a type of disaster risk reduction rather than long-term planning (e.g., response to hurricanes rather than permanent inundation due to sea level rise).[15,127,128,129] For instance, a national survey of metropolitan transit organizations found that most agencies rely on traditional emergency management approaches to address extreme weather during or after the event, rather than advance planning for such events and making changes to preemptively avoid harms.[130] Disaster risk reduction provides an important set of tools and frameworks, but responding to and preparing for permanent changes in climatic conditions requires a different set of approaches than reactively responding to extreme events or sudden hazards. In the long term, an overemphasis on incremental adaptation can lead to maladaptation, where efforts to address climate risk unintentionally increase risk.[99,100] A classic example is that using more air-conditioning to deal with rising temperatures and extreme heat events may increase fossil fuel consumption (if the electricity is generated from fossil fuels), contributing to more climate change and even higher temperatures.

Other incremental adaptation actions may displace risk,[131,132] such as when one home is elevated on a filled mound that pushes rain and floodwaters onto neighboring homes, or have unintended consequences, such as reducing motivation to engage in adaptation (KM 12.4). An emphasis on financially conservative "no regret" decision-making, which limits current costs and prioritizes adaptation options that would be justified under all plausible future climate scenarios, may lead to less expensive but less effective actions.[15,90] Local governments, individuals, communities, or businesses may have insufficient capital to cover the up-front costs of transformation even if those actions would produce long-term gains (KMs 31.5, 31.6). For example, in the short term, reducing agricultural water use through improved irrigation (an incremental change) is cheaper and easier than fundamentally reimagining how and where crops are produced, stored, and transported across the US (transformative change). However, improved irrigation may be insufficient to adapt to long-term effects of climate change and may be less cost-effective in the medium and long term than more transformative options.[27,121]

Climate change will cause both chronic shifts in baseline conditions—such as rising temperatures, sea levels, and water insecurity—and acute risks through extreme events and increased variability (Chs. 2, 3), and these effects will interact with and compound multiple complex (Ch. 18) non-climate stressors such as public health concerns (e.g., pandemics, epidemics; Ch. 15), economic events (e.g., recession, depression), and social injustices (e.g., systemic racism; Ch. 18). Complex social, economic, ecological, and technological systems can be challenging to adapt because elements within the systems reinforce and constrain one another.[1,133,134,135] Transformative adaptation—spanning both social and physical systems—may be needed to address the increasingly intense and nonlinear effects of climate change and their complex interactions with multiple non-climate stressors (Ch. 18).[28,40,136,137] Adaptation actions that consider co-benefits where possible (including contributing to climate mitigation but also biodiversity, pollution reduction, social justice, and others) are expected to provide the greatest social gains and long-term sustainability.

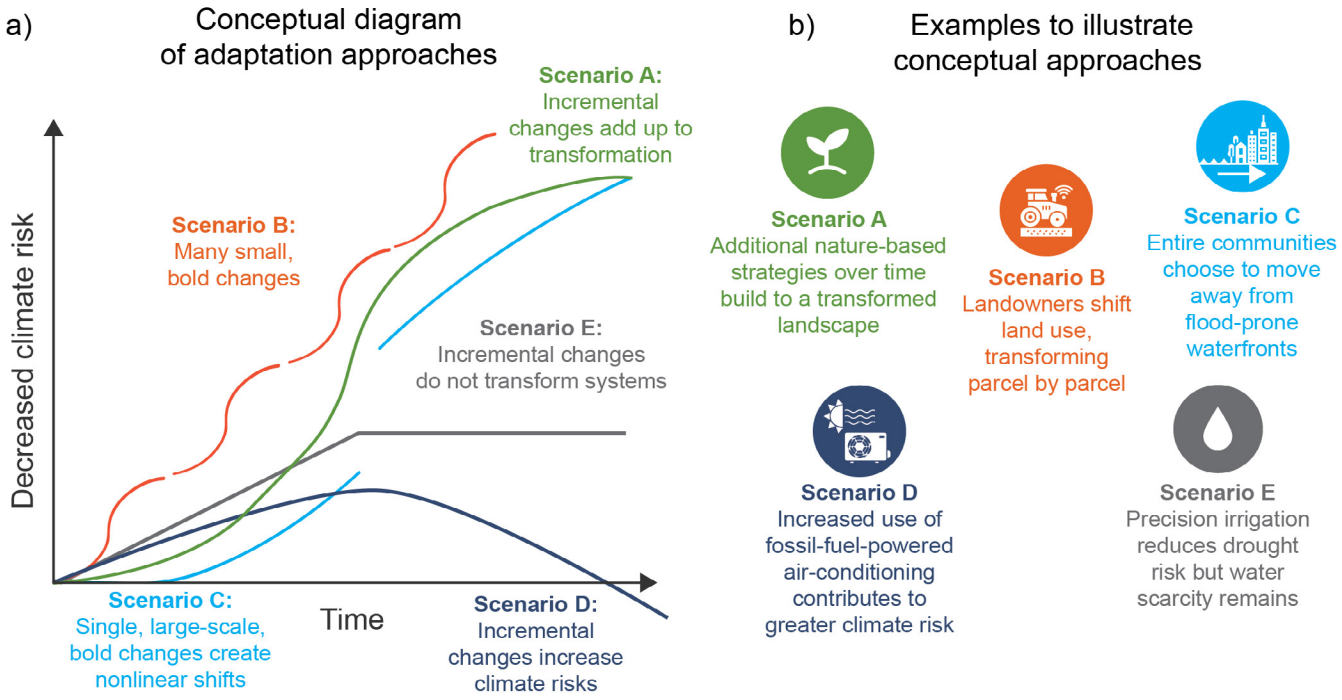
Adaptation may increasingly require a systems approach to focus on how multiple systems (e.g., social, political, cultural, ecological, physical infrastructure, energy, water, food) interact with and shape one another and to identify adaptation actions that cut across or leverage multiple systems.[6,138] Compared with transformative adaptation, most incremental adaptation requires less coordination across interested parties, making it appealing to actors working within a single sector of a larger system and where coordination is difficult to achieve. A systems approach, for example, would consider vulnerabilities across different modes within a system (e.g., highways and public transit) or across systems such as transportation, water, the electric grid, telecommunications, supply chains, stormwater management, and land-use or development patterns. A systems approach to adaptation might argue for adaptation efforts to occur in different government offices (e.g., in transportation planning and housing as well as in emergency management and environmental agencies), for coordination of public and private efforts, or for greater cooperation across silos to support transformative adaptations (KM 31.4). Adaptation actions that take a systems approach to assessing vulnerabilities and adaptation opportunities are expected to be more transformative insofar as they affect multiple systems at multiple scales.[90]

Transformative adaptation may also involve changes to systems and paradigms in ways that redress historical injustices and center equity.[40] Transformative adaptation has the potential to perpetuate or exacerbate social injustices, but inequities are not inevitable.[137,139,140] Addressing them requires express consideration of equity and justice along with direct engagement with disadvantaged and underserved communities (KM 31.2), and lessons can be learned from the "just transitions" literature and movements (Ch. 20; KM 20.6).[108,141,142,143] For example, transforming car-centric transportation systems to emphasize public transportation and walkability could increase accessibility for underserved communities and people with limited mobility if the transformation intentionally includes user input to address accessibility and equity from the start. Transformations may also advance equity by reforming systems and institutions that perpetuate inequities. For example, the reliance of local governments on property tax revenue as a major source of funding has contributed to disaster risk reduction and adaptation governance systems that sometimes prioritize protection of property values rather than people or ecosystems.[144,145] Transformations to these and similar underlying systems may be needed to address climate adaptation equitably.[40] Congressional efforts to reform to the National Flood Insurance Program, for example, have struggled to balance, on the one hand, the need to increase premiums and enrollment to accurately reflect risk and, on the other, the need to keep premiums affordable. Solutions to this problem may require broader transformations in the way insurance and risk information are provided.[146,147,148] Transformative actions are also expected to be necessary to address numerous systemic inequities such as colonialism, systemic racism, wealth inequality and distribution, and economies based on extractive industries.

Adaptation actions are not divided distinctly between incremental or transformative actions (Figure 31.3). In some cases, incremental adaptation actions add up to transformative change if they are widespread enough; however, the place-based nature of adaptation can make this particularly difficult to achieve. In others, incremental adaptation can lead to a limited degree of change that may be insufficient in the face of future climate conditions. Similarly, transformative adaptation can take different forms (Figure 31.3). The exact blend of incremental and transformative actions that will be needed across the United States is not clear, but given the current predominance of incremental action, it is expected that future adaptation will need to include more transformation. The more and faster the climate continues to change (e.g., if global greenhouse gas emissions are not aggressively cut in the near term; Ch. 32), the more severe and spatially uneven climate change impacts will be and the more transformative adaptation will be needed at greater rates, scales, and extents. Transformation and even creative incremental adaptation may be able to overcome soft limits—challenges such as affordability that may be surmounted with additional research or investment—but if global emissions continue unabated, systems and communities will eventually encounter hard limits, points beyond which adaptation cannot avoid intolerable risks and impacts.[149,150]

The pros and cons of different types of adaptation are difficult to compare because adaptation, in general, is difficult to evaluate since it involves measuring harms that do not occur (e.g., avoided losses). Assessments of the effectiveness of adaptation actions have generally been limited to project-specific performance against a limited set of extreme events or climate conditions.[32,151,152,153,154] Adaptation researchers and practitioners have begun to track the number of actions that have occurred across the US and to evaluate adaptation projects in a limited manner (KM 31.1; Figure 31.1). However, efforts to assess trade-offs, effectiveness, sufficiency, and long-term consequences of incremental and transformative adaptation actions are still largely theoretical and will need more work to implement and consistently track over time. Metrics will need to be granular enough to observe disparities among communities to reduce potential inequities.[32,33]

## Incremental and Transformative Adaptation Approaches




**Incremental and transformative adaptation may take many forms, but incremental adaptation involves small changes while transformative adaptation involves profound shifts.**

**Figure 31.3.** (**a**) Adaptation actions can involve small changes to business as usual (incremental) or bold measures that break from past practices and create new systems (transformative). In some cases, incremental changes may add up to a transformation of the overall system (Scenario A). In other cases, they may not (Scenario E), or they may even cause maladaptation (Scenario D). Transformative adaptation can also take different forms, including a series of small-scale transformations (Scenario B) or larger one-time shifts (Scenario C). Neither incremental nor transformative adaptation is always preferable, and both approaches may exacerbate injustices if equity is not centered (KM 31.2). The examples in panel (**b**) illustrate these conceptual approaches to incremental and transformative change; each could be equitable if it follows the principles of equitable adaptation. Current adaptation practices in the US are predominantly incremental and do not clearly add up to system-wide transformation. Adaptation in the future, therefore, is expected to require a greater degree of transformative adaptation in the overall portfolio. Figure credits: (a) adapted with permission from Fisher and Williams 2020;[155] (b) University of Delaware and National Institute of Standards and Technology.

## Key Message 31.4

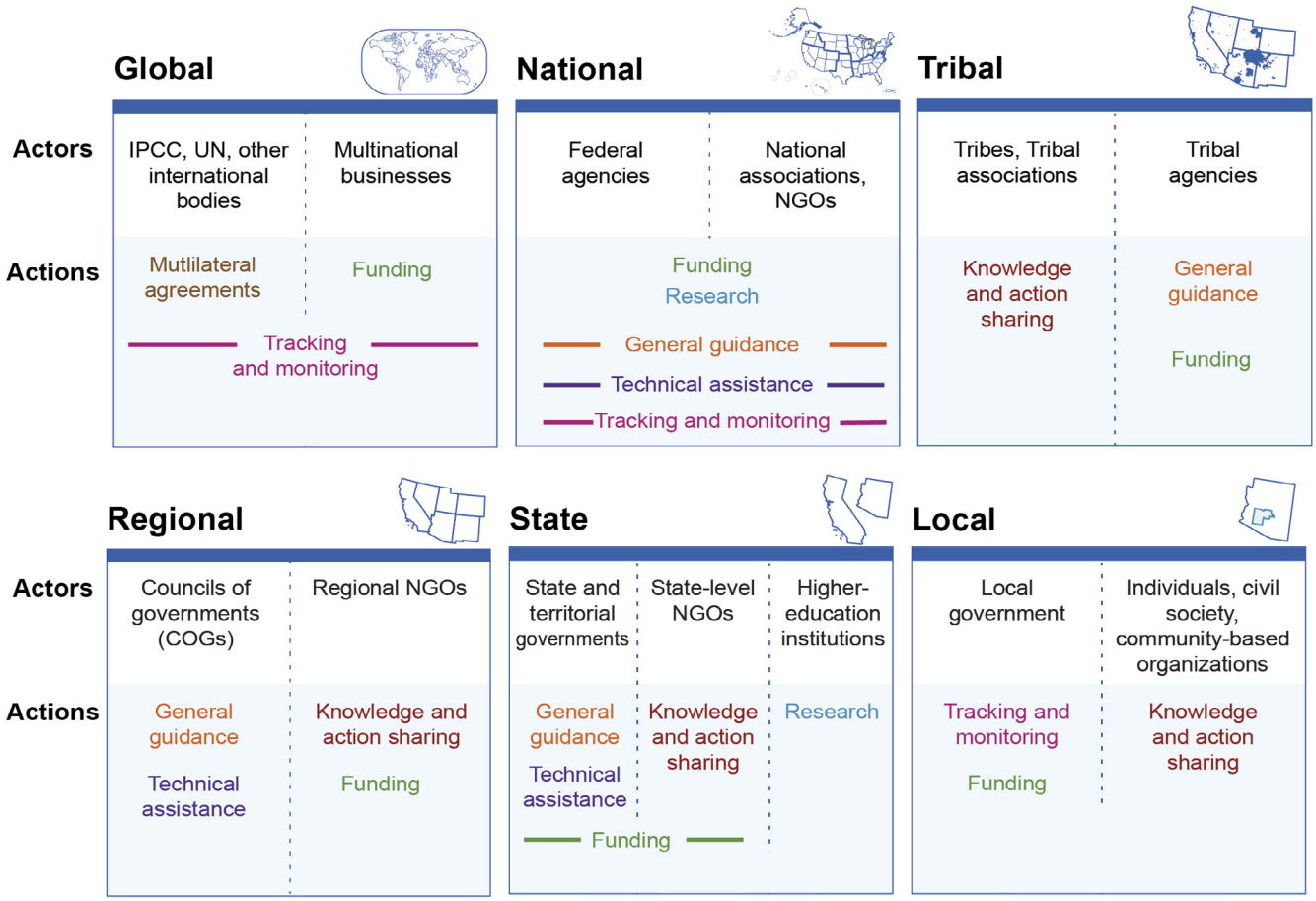
## Effective Adaptation Governance Empowers Multiple Voices to Navigate Competing Goals

Adaptation involves actors from government, private-sector, nongovernmental (e.g., nonprofit and for-profit institutions), and civil society organizations, which often have different priorities and approaches (*high confidence*). Adaptation decision-makers must balance competing goals while also addressing uncertainties regarding future climate change and the ways that political, social, and technological systems will be transformed (*high confidence*). To minimize the potential for adaptation actions to benefit some at the expense of others, adaptation processes must emphasize collaboration, center equity and justice, and incorporate a wide range of values and knowledge sources (*medium confidence*).

Governance refers to the structures and processes used by governments and other decision-makers to develop and implement policies, programs, and institutions.[156] Compared to many policy fields, formal governance of adaptation is relatively underdeveloped, with weakly defined ambitions, responsibilities, routines, and evaluation methods and no overarching federal policy framework for adaptation.[157,158] Nonetheless, numerous organizations are engaging in adaptation governance in a more bottom-up fashion.[15,40] For example, urban flood management may be directed by local actors coordinating activities without a higher-level directive.

Many different types of organizations make decisions about adaptation, including federal, state, territorial, Tribal, and local governments; businesses; nonprofits; households; and individuals—all with variably overlapping jurisdictions (Figure 31.4). While some adaptation decisions are made unilaterally, such decisions often involve multiple organizations; adaptation networks have become more complex in the last decade, involving more actors from more diverse organizational backgrounds.[159] The actors involved often have distinct (and at times conflicting) views of the problem, risk tolerance levels, priorities, preferred solutions, and ideal futures.[160,161,162,163,164]

## Organizations and Actors in Adaptation Governance




**Climate adaptation involves numerous actions by different actors at multiple jurisdictional scales.**

**Figure 31.4.** Climate adaptation governance occurs at multiple scales, with numerous government, private, and civil-society organizations supporting adaptation through funding, guidance, and other activities. While all actors can directly implement adaptation activities, activities implemented in a coordinated fashion and with technical assistance, funding, and monitoring provided by actors across sectors and scales have the potential to be more effective and transformative. Figure credit: University of California, Irvine, and National Institute of Standards and Technology.

When organizations have an explicit focus on adaptation, they tend to organize their governance activities in diverse ways. For instance, some cities, states, and utilities have created centralized offices focused on overall resilience and/or sustainability, while others have distributed climate adaptation tasks across critical functions, each focusing to varying degrees on hazards, social resilience, and/or environmental protection.[165] At the federal level, legal frameworks for climate adaptation cover a broad range of agencies, and these agencies may differ from those mandated to conduct research on the efficacy of adaptation governance (e.g., Executive Order 14008, Section 203[118]).

Given this complexity, adaptation governance is often fragmented and uncoordinated, with the diverse actors operating independently and ignoring potential side effects or spillovers.[48,49,50,51] This problem exists even in settings where actors recognize the need for more coordinated governance.[166] Finally, while there is increasing recognition of cross-jurisdictional impacts, fragmented governance systems are not structured to handle impacts that cross geographic borders.

Leading practices in adaptation governance are based on credible science and involve ongoing open processes to support multiple voices across government, civil society, and expert advisors (Ch. 2).[156,167,168]

Linking adaptation policy and governance involves timely and salient communication across actors, involving media, lobbyists, and boundary organizations that help translate scientific information and co-develop technical support relevant to local communities.[169,170,171]

Effective and equitable adaptation governance also benefits from intentional engagement and coordination among all involved actor groups over a sustained period.[1,51,165,172,173] For example, following multiple wildfires and postfire floods, Santa Clara Pueblo collaborated with multiple federal agencies, the state of New Mexico, and several other Tribes to restore their watershed and build resilience against future floods.[174] Such collaboration is particularly effective when a single government agency leads coordination of an interorganizational group to oversee adaptation activities.[175,176,177] Alternatively, coordinating hubs can help bridge activities of disparate actors;[178] having well-defined roles and responsibilities can avoid duplicated efforts.[165] However, federal agencies can face administrative barriers when engaging with community and nongovernmental actors, such as the Paperwork Reduction Act's requirement of extensive documentation when collecting information from the public.

Well-functioning, multilevel governance helps in adaptation strategy development.[179,180] For example, California, Florida, and other states have used informal regional collaborations (e.g., Southeast Florida Regional Climate Compact, Alliance of Regional Collaboratives for Climate Adaptation) to share resources and develop adaptation strategies that serve regional needs. The Coastal Zone Management Act,[181] which requires federal, state, territorial, Tribal, and local coordination in a single review of newly developed laws beyond borders to protect and develop coasts, is a potential model for encouraging greater cross-scale actions. Vertical linkages between governance levels can help bridge the gap between community-based and national-level adaptation efforts[179] and enhance horizontal linkages across public and private actors and institutions. Horizontal network linkages enable diffusion of information and resources across similar organizations; for example, horizontal connections between community groups facilitate selective adoption of context-specific adaptations and the scaling out of successful adaptation actions.[182]

In instances when adaptation governance brings together groups that traditionally have not worked together, guidance from conflict resolution and collaborative governance can help.[183,184] Ensuring that decision-making processes regarding adaptation planning and implementation are inclusive is necessary to enable a just and equitable distribution of burdens and benefits (KM 31.2). Additionally, adaptation decision-making structures are most effective when they allow for innovation, learning, feedback, and continual improvement.[165,173]

At the federal level, much adaptation has been governed through disaster policies (e.g., through FEMA hazard mitigation planning and grants and HUD disaster recovery grants).[185,186] These policies may not be adequate or appropriate for long-term and systemic adaptation because they are often framed in ways that may not address local adaptation needs and focus mostly on critical infrastructure and disaster response rather than institutional change.[187] Either those systems will need to be transformed or new systems will need to be developed for the US to adequately adapt to future climate hazards.

Another key issue in adaptation governance tends to be unfunded mandates or responsibilities assigned to regions or communities without dedicated increases in funding and capacity.[1,188,189] Government-led adaptation planning would benefit from a greater focus on understanding community-driven adaptation before making significant resource-allocation decisions, given the inherently local nature of adaptation.[190] Development of enabling conditions and frameworks to support adaptation is best guided by recognizing local values, competence, interest, awareness, and analytical capacity.[171,191]

Most governance institutions were created when climate change was not recognized and the climate system was relatively stationary.[123,192] New and revamped governance arrangements face tensions with structures of pre-existing institutions that are strongly embedded and may be protected by long-standing power

dynamics.[123,193] Creating adaptive systems will require fundamental changes across multiple systems and sectors, such as infrastructure, agriculture, public health, and natural resource management (KM 31.3; Chs. 6, 11, 12, 15, 18). Additionally, transformative adaptation benefits from aspirational vision and leadership, as transformative adaptation can upend existing norms and practices.[194]

Systemic change can be facilitated through changes in laws, codes, and standards; data collection (e.g., disaggregated demographic data); and regulations that shape decision-making for intentional and equitable adaptation. For example, laws requiring cost–benefit analyses prioritize infrastructure investments in neighborhoods with high-value properties unless explicit practices to target specific beneficiaries are included and the disaggregated data to identify desired beneficiaries exist.[195,196] Likewise, laws that prescribe the types of science used in decision-making may exclude local or Indigenous Knowledge, limiting both participation in decision-making and incorporation of multiple actors' views and priorities (KM 16.2).

The body of research to inform effective and equitable adaptation governance is growing, but knowledge gaps and a need for translating research findings into on-the-ground implementation action remain. Adaptation researchers can inadvertently create gaps, make translation more difficult, or duplicate efforts if they do not fully reference previous works or if the field becomes too fragmented across disciplinary or topical silos.[197] Local governments can prioritize adaptation activities and avoid maladaptation and unintended side effects by effectively identifying and assessing synergies and trade-offs that are context specific.[198,199] Building local capacity can also support more equitable adaptation governance.[197] Research on adaptation governance may increasingly address a rise in climate litigation, with thousands of US cases identified in climate litigation databases.[200] A key driver for litigation is compensation for the costs of adaptation. The dynamic sociopolitical and scientific context in which climate litigation takes place makes it challenging to assess its impact.[201] Finally, identifying institutional and systemic shifts that may support more coordinated and transformative governance would require more research.

## Key Message 31.5

## Adaptation Requires More Than Scientific Information and Understanding

Effective adaptation to a changing climate requires both decision-relevant climate information and evidence-based decision-making approaches (*high confidence*). Adaptation requires that researchers intentionally collaborate with communities to identify goals, assess vulnerability, improve capacity, and address contextual factors, such as values, culture, risk perception, and historic injustices (*medium confidence*). Climate services can be improved by ensuring access for historically disinvested communities and by attention to procedural and recognitional equity when scientists work with communities and decision-makers (*medium confidence*).

Climate data and information remain a limiting factor for adaptation. However, many people and organizations, especially those in historically disinvested communities, require more than scientific data and information to adapt.

Cities and states use climate data, information, and decision-support tools in adaptation decisions (Table 31.2) to, among other things, identify, assess, plan, and reduce risks. For example, the city of New York recently legislated Climate Resiliency Design Guidelines,[202] which, among other things, determine the height of flood protection measures using climate projections from the New York City Panel on Climate Change. Tools like the US Climate Resilience Toolkit,[203] Climate Mapping for Resilience and Adaptation,[204] the Sea Level Projection Tool,[205] and even the web-based format of the National Climate Assessment (NCA)[206] provide broad access to climate information across the US. Several states have developed climate data portals to

provide communities with location- and sector-specific climate hazard data (e.g., Cal-Adapt in California,[207] the New York Climate Change Science Clearinghouse,[208] and the New Mexico Climate Risk Map[209]). These tools are particularly useful for organizations with the technical and technological expertise to interpret and customize the data (e.g., insurance companies, larger cities and states, and other entities). However, many adaptation decisions are made without customized adaptation decision support,[162,210] which may be due to the overwhelming number and complexity of tools that exist.

A growing number of efforts provide science- and evidence-based support that extends beyond climate data and information. These efforts are referred to by many names, including climate services,[47,211,212,213,214] technical assistance,[215,216] decision support,[217] sustained assessment,[218] and boundary spanning.[219,220] These terms are not synonymous in that they have distinct approaches related specifically to adaptation that go beyond technical support. These various efforts might

- consider context and need in early stages of development to increase scientific adequacy and to respect processes of knowledge creation involving people with diverse values and lived experiences;[211, 221,222,223,224,225]
- honor Traditional Knowledge systems[226] and Indigenous self-determination (KM 16.2);
- address contextual factors such as risk perception, decision-making authority, and organizational agility;[227,228,229]
- customize data and information to fit the time frame and spatial scale of interest;[222,229,230]
- manage uncertainty about the extent and timing of climate change and its effects, as well as about potential social–economic–environmental futures;[161,231,232,233,234]
- plan for and anticipate multiple possible futures to respond to changing conditions and unforeseen consequences;[235,236,237,238]
- strengthen public participation and democracy by engaging multiple actors in negotiating goals, evaluating trade-offs, and making adaptation decisions (KM 31.3);[10,84,227,239,240,241,242,243,244] and
- develop evidence-based strategies for changing behaviors and systems and evaluating outcomes.[151,245,246,247,248]

There are several Federal programs that provide broader forms of climate decision support. For example, NOAA's Climate Adaptation Partnerships Program, USDA's Climate Hubs, USGS's National and Regional Climate Adaptation Science Centers, National Park Service's Climate Change Response Program, EPA's Environmental Justice Thriving Communities Technical Assistance Centers, and Department of Energy's national labs[47,249] all provide climate services for a range of sectors and regions. Similarly, the Tribal Climate Adaptation Menu (Dibaginjigaadeg Anishinaabe Ezhitwaad),[250] developed by numerous stakeholders in Minnesota, provides a framework to integrate Indigenous and Traditional Knowledge into the climate adaptation planning process. Despite these existing efforts, there are still limitations on awareness of and access to services, especially for historically disinvested communities.

Access to broader forms of technical support varies, with underserved communities facing critical gaps (KMs 16.2, 29.4). Not all regions are covered. Some sectors are further along in climate adaptation planning than others. While there has been some research on gaps by region and sector,[249] no comprehensive nationwide evaluation exists that assesses the availability of climate services, and most existing evaluations are largely based on geographic and sectoral coverage, not differential exposure and factors related to social vulnerability. Moreover, many emerging forms of support are not explicitly focused on climate services. Instead, they are providing climate-related technical assistance, which is unfamiliar to some environmental justice communities and Tribal Nations.[215,216,251] Additionally, environmental justice communities and Tribal Nations face barriers to obtain federal funding for technical assistance because there is a high level of

technical skill required to apply and/or strict eligibility criteria.[252] When, how, where, why, and for whom climate services and climate-related technical assistance are distributed can be tied to transformative and equitable adaptation (Table 31.2).

**Table 31.2 Climate Services Can Be Designed to Support Transformative and Equitable Adaptation**

Climate services can be aligned to the level of community engagement and the impact of adaptation efforts. Climate services are not about supporting decisions in a vacuum. They can be designed to avoid engagement fatigue and advance transformative adaptation. Climate services can assess vulnerability and adaptive capacity to support actions to reduce unjust, maladaptive choices. Engaging communities in the development of climate services related to adaptation can empower environmental justice communities and Tribal Nations. Data and information tools can help reduce engagement fatigue if the goals, outcomes, and values have been established. If community engagement is needed to codevelop goals and values necessary to evaluate the consequences of transformative adaptation options, institutional partnerships can build and sustain the inclusive participation of diverse community voices.

| Level of Community Engagement in Climate Services | Incremental Approach to Adaptation | Transformative Approach to Adaptation |
|---|---|---|
| Low | **Are services enabling maladaptation?** Consider services that assess vulnerability and adaptive capacity to account for injustices. | **Are services supporting equity?** Consider services that remove barriers to participation in climate adaptation, including knowledge generation. |
| High | **Are services operationalized?** Consider services that provide decision tools to reduce engagement fatigue. | **Are services sustained and mainstreamed?** Consider institutional arrangements that maintain trust, credibility, and saliency and embed services into decision processes. |

Adaptation decisions range from smaller-scale, incremental decisions with clearer and limited participants to far-reaching, transformative changes with multiple decision points and decision-makers. Climate services can support adaptation and equity by encouraging discussion between historically disinvested communities and decision-makers regarding relevant climate risks and trade-offs between adaptation options.[56,253,254,255] In some cases, the trust and relationships built through an inclusive decision-support process lead to collective learning and adaptation over time, sometimes referred to as coproduction.

Coproduction encompasses a range of collaboration modes—from consultative to collegial—that structure science and decision support to advance societal goals.[151,227,247,248,256,257,258] Coproduction involves iterative, multiway processes that can strengthen procedural equity through power sharing and collaborative knowledge creation. For example, Looking Forward, Looking Back: Building Resilience Today, a partnership between the Alaska Climate Adaptation Science Center and the Aleutian Pribilof Islands Association, involved five community teams with leaders from each spanning multiple governing bodies, including the Tribal Council, the city governments, and the village corporations.[259] Training and workshops in each community were designed to support the development of climate adaptation plans.

Coproduction needs to be structured in ways consistent with the need and potential adaptation impact (Table 31.2). Coproduction is time- and resource-intensive, which can be another burden on disinvested communities,[260] especially given that language differences, remote locations, and other logistical challenges (e.g., lack of childcare) present barriers to participation and engagement. Additionally, there is a risk of unintentionally creating competing and unaligned goals across community members, technical experts, and government officials.[227] There are also often mismatches between the urgency for climate action, the long-term development of scientific evidence, and governmental decision processes.

To improve adaptation practice, adaptation-needs assessments—not solely focused on science gaps but also on adaptation barriers—can identify how practitioners and communities are or are not supported by

the scientific community in their adaptation efforts and in what contexts different forms of support are preferred over others.[261,262,263]

In particular, decision-makers can benefit from access to or the development of methods, metrics, and indicators (App. 4.7) that support trade-off analysis when making adaptation decisions.[264] Additionally, to evaluate adaptation choices, decision-makers can

- use these tools to track progress on adaptation efforts and outcomes;[33,153]
- assess short-, medium-, and long-term adaptation effectiveness;[151,152,265] and
- evaluate the advantages and disadvantages, including cost-effectiveness, of incremental and transformative adaptation.[152,154]

Although vulnerability indicators have been developed and thoughtfully used in planning efforts,[266,267,268] and resilience indicators have gained traction recently to assess community impacts or resilience factors,[269,270,271] adaptation indicator development has lagged, because assessments of effectiveness and comparisons against baselines have been limited to evaluation of specific projects.[32] Indicators need to consider context, audience, and use to be effective, including the multiple ways that adaptation affects communities and ecosystems. For example, building a seawall may reduce the likelihood of floodwaters reaching the homes behind the wall (risk outcome), but the wall may also increase erosion of neighboring properties (risk outcome to people outside the wall), narrow the beach and affect coastal species (environmental outcomes), and cut off access to the shore, changing the way people in the community interact with the coast (social outcomes).[93,272]

## Key Message 31.6

## Adaptation Investments and Financing Are Difficult to Track and May Be Inadequate

Investments in adaptation are being made at the federal, state, territorial, Tribal, and local levels, as well as within the private sector, but they are not always evenly distributed, coordinated, tracked, or reported (*high confidence*) and may be inadequate (*medium confidence*). Future adaptation investment needs are expected to be significant, although projected amounts vary due to uncertainty in future emissions trajectories, associated impacts, and the timing of implementation (*high confidence*). Proactive adaptation can reduce some of the most severe costs of future climate change, particularly under very high emissions scenarios in the late 21st century (*medium confidence*), although adaptation is still needed in the present for communities and infrastructure that may not be well adapted to face current climate conditions (*high confidence*).

Estimates of the damages and associated costs of climate change without adaptation can reach into the hundreds of billions of dollars by the end of the century (Table 19.1).[273,274] Although there are national-level estimates of the economic cost (total damage) of climate change (Ch. 19),[273] there are no comprehensive national-level estimates of adaptation costs for the US. Across adaptation economics assessments, there is little consistency regarding which future emissions scenarios are considered in projecting impacts, the sectors evaluated, the types of damages considered (e.g., direct and/or indirect), the time horizon for cost estimates, and the costs of implementation.[1,275] Despite these differences, studies in the US consistently project adaptation costs on the order of hundreds of millions to billions of dollars.[273,274,276,277,278,279]

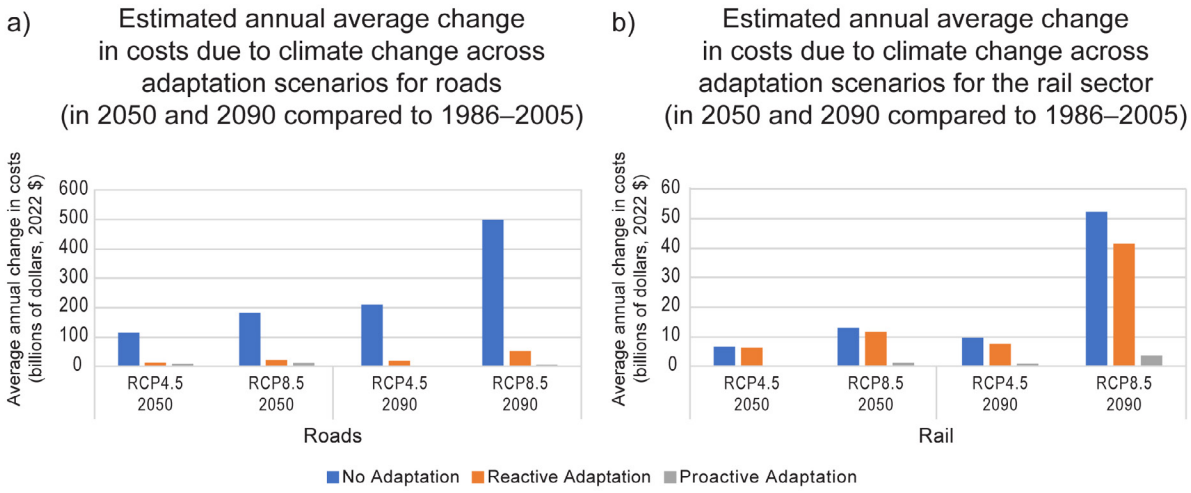
Determining how much and where to invest in adaptation involves decision-making under uncertainty, evaluation of trade-offs, and assessment of the risks associated with delaying action. Generally, this involves quantifying the projected economic impacts of climate change (KM 19.1), the projected costs of adaptation actions, and the expected benefits and/or avoided harms from those actions, all of which can be deeply uncertain. Other essential considerations include efforts to determine ideal levels of adaptation given resource constraints and how to efficiently and equitably allocate costs and benefits among stakeholders. Considerations that are implicit or explicit in adaptation-related economic analyses include questions of who pays for or benefits from adaptation, how to account for the nonmonetary or difficult-to-quantify costs of climate change (e.g., the emotional and physical toll of experiencing extreme weather events, displacement of community after an event, loss of traditional ways of living, and loss of sites of cultural significance; KM 19.1), and what stakeholder interests are reflected in the valuation (both cross-sectionally, in terms of different stakeholder groups, and temporally, as in the choice of discount rate). Some organizations have generated benefit–cost ratios to reduce the impacts of climate hazards through adaptation planning. For example, the National Institute of Building Sciences suggests a 4:1 benefit–cost ratio for hazard mitigation work, with federal grants spent on resilience achieving a 6:1 benefit–cost ratio.[280] However, even when adaptation implementation is favored, other factors such as finances, risk perceptions, inadequate incentives, community capacity, competing priorities, or social and political influences may lead individuals and communities to underinvest.[279,281]

Improvements have been made in the ability to quantify and monetize the physical impacts of climate change (KM 19.1), which are used to estimate both the costs and value of various adaptation actions,[273] although uncertainty and limitations in these estimates remain.[150,282,283] Estimating the aggregated and disaggregated (e.g., sectoral or regional) costs of adaptation, risks of inaction, and value of adaptation actions involves several methodological challenges:[284] developing damage functions that represent impacts of climate change and account for adaptation;[282] understanding the limits of adaptation options and capacity (e.g., effective options may not be presently known or adaptation limits may have been reached); analyzing the behavior of different cost estimation methodologies across climate scenarios and time horizons; incorporating the context specificity of adaptation choices and outcomes into analysis, especially at larger scales (KMs 31.2, 31.4);[285] and evaluating the effectiveness and sufficiency of the actions taken to adapt to climate change.

Both the Fifth and Sixth Assessment Reports of the Intergovernmental Panel on Climate Change state that the benefits of adaptation are expected to be larger than the costs.[284,286] However, both reports note important limitations in estimating aggregate climate damages, costs of adaptation options, and avoided damages from adaptation implementation that create uncertainty and can make it difficult to compare across studies (Cross-Working Group Box Economic in O'Neill et al 2022[150]). Proactive adaptation (e.g., actions, which can be transformative or incremental, taken with the goal of preventing repair costs associated with future climate change) has been shown to reduce climate change damage–related costs for some sectors compared to reactive adaptation (e.g., repairs to damaged infrastructure that do not generally include consideration of future climate change but do consider current climate conditions; Figure 31.5)[128,274,277,281] or no adaptation. In the context of electricity distribution infrastructure, for example, proactive adaptation might entail updating wooden pole designs to account for expected temperature and precipitation conditions over the full future life span of the asset.[128] Reactive adaptation would entail replacing the poles with designs that are only reflective of current climate; no adaptation would entail using designs that do not account for any climate change that already may have occurred.[128]

Despite the estimated value of proactive adaptation, real-world impediments to proactive adaptation, such as ill-timed revision of infrastructure codes and inadequate incentives, can inhibit feasibility of implementation,[128,274] and findings may not be applicable in all sectors.[273] In many studies, proactive adaptation becomes increasingly valuable with greater levels of warming (e.g., under higher emissions scenarios), with benefits accruing over time, particularly in the later decades of the 21st century.[274,277] Where there is considerable current risk to infrastructure and assets from climate conditions (e.g., flood-related risk), it can be cost effective to implement adaptation now even if future benefits from proactive adaptation are small when discounted to the present.[279]

## Estimated Annual Change in Costs Due to Climate Change




**Future costs associated with climate change will depend on adaptation efforts and scenarios.**

**Figure 31.5.** In some sectors, proactive adaptation can help reduce projected damages from climate change. Estimates are shown for a 5-model ensemble for two sectors (roads [**a**] and rail [**b**]), two time periods (2050 and 2090), and two scenarios—an intermediate scenario (RCP4.5) and a very high scenario (RCP8.5). The three adaptation scenarios reflect the nature in which adaptation has been implemented. Estimates include only costs incurred above historical climate conditions (e.g., climate conditions associated with historical climatology) and assume that adaptation can be readily implemented. Findings should be interpreted only for the sectors shown. Adapted from Neumann et al. 2021[274] [CC BY 4.0].

The scale of the adaptation challenge requires multiple streams of investment (personal, private, and public) and multiple financing options for individuals and communities that may struggle to finance it on their own (KM 21.5). Investments in adaptation[287] are being made at the federal, state, territorial, Tribal, and local levels, as well as within the private sector, but they are not always evenly distributed, coordinated,[288] tracked, or reported.

Adaptation finance relates to monetary investments that reduce the vulnerability or increase the resilience of human and ecological systems to negative climate change impacts.[289] Funding for adaptation, which to date has traditionally originated within the public sector, lags financing for mitigation-related projects (e.g., renewable energy development, energy efficiencies).[275,290,291,292] In addition, adaptation funding is tracked and reported more transparently at the international level than in the US, both in terms of total volume of investment and flows between countries.[284,291] In 2019 and 2020, the annual average of global adaptation finance investments was approximately $55 billion, compared to $659 billion for mitigation projects (in 2022 dollars).[291] Funding is largely funneled through public lending institutions such as multilateral and national

development finance institutions but can also originate from other sources, including commercial finance institutions, governments, and corporations. Tracking of domestic public-sector and overall private-sector adaptation-related investment and financing is a known gap.[284] However, given their cross-cutting nature and co-benefits, investments in adaptation are not always clearly demarcated or obviously identified, making it difficult to explicitly track them and ultimately evaluate their effectiveness. Funding for infrastructure hardening, home weatherization, or cooling centers, all of which can be considered adaptation-related investments (and more incremental), may come from diverse organizations, be dispersed across programs, or not be clearly tagged as adaptation-related expenditures.

Federal and state budget and expenditure tracking does not always distinguish between mitigation- and adaptation-related activities (Box 12.1).[25] Assessing the landscape and uptake of available financing instruments can illuminate where adaptation finance presently originates and is concentrated. Several toolkits, such as the Equitable Adaptation Legal and Policy Toolkit[287] and Ready-to-Fund Resilience Toolkit,[293] provide an overview of different funding (e.g., government grants) and financing (e.g., debt or equity financing) options that are available and help communities design and finance adaptation projects. Services from network organizations such as the American Society of Adaptation Professionals facilitate exchange of leading practices and collaborative spaces for trusted partnerships to form and co-investments to occur for climate adaptation. Understanding how to utilize funding sources would also require understanding levels of vulnerability, hazard exposure, and adaptation and resilience requirements in a future climate context.

At the federal level, government entities such as the Department of Treasury and FEMA provide grants and manage national tax credit and similar financing programs. Other Federal Government entities such as the Department of Transportation, NOAA, and the Department of Energy fund projects to advance adaptation at various levels of government and sectors (KMs 5.3, 9.3, 13.1).

Private-sector investments in adaptation can include funding or financing options (e.g., grants from private and philanthropic organizations, impact investing from private and development finance institutions, incentives for adaptation measures from insurance companies [KM 21.5], and/or loans from green banks), as well as direct investments from private companies to implement adaptation measures to reduce physical climate risk. There has been increased activity in the private sector exploring adaptation to physical and transition risks. This activity has been driven partially by investors requesting increased transparency in climate-related and environmental, social, and governance impacts (e.g., the Task Force on Climate-related Financial Disclosures) and ranges from climate risk disclosure to organizational resilience and from capital stress testing to adaptive asset management. Private-sector organizations have also made independent and regulatory-required adaptation-related investments after natural disaster events (e.g., asset hardening after a severe storm). With limited information on corporate and other private-sector adaptation, it is hard to know the scale and sufficiency of actions implemented to date, but overall, adaptation planning and investments appear to lag significantly behind low-carbon transition planning.

Data on corporate and other private-sector investments in adaptation are very limited, in part due to confidentiality restrictions, uncertain causality, and lack of agreed-upon impact metrics.[275,294] Lack of data makes it difficult to determine where private-sector investment is occurring and any gaps in sectoral, geographic, or community access to privately funded opportunities. Investments in adaptation by the private sector may face more hurdles due to greater challenges with quantifying return on investment compared to mitigation-related projects, uncertainty in policy and regulatory environments, mismatched investment time horizons, and challenges in mapping climate impacts to business-related activities.[57] Increasing transparency in climate-related disclosures that describe the actions corporations and other private-sector entities are taking to minimize the physical and transition risks to their organization, their value chain,

and the communities where they reside and operate may advance the ability to track action and progress toward adaptation where climate risks are extensive. Concerns remain, however, about the comprehensiveness, alignment, and quality of information included in disclosures, as well as the ability to compare across responses.[295] Responses also overwhelmingly skew toward large corporations in specific sectors, in part due to the significant resources required to prepare disclosure responses.[295]

In practice, there are multiple examples of communities leveraging the diversity of investment instruments, risk finance mechanisms, and broader finance-relevant solutions to support adaptation. Examples include federal and state public funding (e.g., Louisiana's Strategic Adaptations for Future Environments program[296]), municipal public–private funding (e.g., DC Water's Environmental Impact Bond[297]), development institution investment (e.g., Coastal Enterprises Inc., a community development financial institution based in Maine[298]), and public–private risk transfer (e.g., a parametric insurance program for the Miami-Dade School District, developed by reinsurer Swiss Re). Financial instruments can serve multiple purposes—to finance activities that reduce direct exposure and vulnerability to physical climate change impacts and to transfer and/or reduce risk where physical climate impacts are difficult to eliminate through more direct measures (e.g., through insurance and other instruments). In late 2022, the 117th Congress passed the Community Disaster Resilience Zones (CDRZ) Act[299], requiring FEMA to continue to maintain a natural hazard assessment program, designate community disaster resilience zones based on census tract hazard-risk ratings, and provide an increased federal cost share to those communities. The CDRZ Act is an amendment to the 1988 Stafford Act,[300] requiring the identification and improvement of the climate and natural hazard resilience of vulnerable communities. FEMA will engage with state, territorial, Tribal, and local emergency management partners to identify how the designation of the zones can benefit these government entities.

Despite these and other actions, several gaps limit the efficacy and volume of adaptation finance in the US, including the following:

- **Challenges in tracking and assessing adaptation finance flows:** As previously stated, sparse data on public and private adaptation-related investments inhibit the ability to track finance flows and overall investment levels within the US. Work to establish a process for tracking these data would be an important first step in better understanding the sufficiency and efficacy of adaptation investments. Adaptation finance gaps are also generally assessed in terms of aggregated finance volume (e.g., a country or regional average of adaptation finance), which does not capture the efficacy of finance.[301] Impact metrics are crucial for a full accounting of adaptation finance.
- **Upfront or operational costs of adaptation are, or are perceived to be, high or are inhibited by other factors:** Many interventions that could strengthen adaptation have, or are perceived to have, high up-front costs or uncertainty in total costs (especially if the costs or benefits are difficult to quantify) and may not be viewed as viable within many institutions' or communities' financial capacity. Local adaptation plan cost estimates sometimes exceed local governments' entire municipal budgets,[302] leaving very little budget to implement the actions identified in the plan.
- **Private entities have historically lacked incentives to invest in adaptation, but this may be changing:** Investments in adaptation can be perceived as public goods, limiting private-sector involvement.[57,286] Many private financiers have faced difficulties incorporating the economic benefits from avoided losses into their investment decision-making.[303] Emerging evidence points to increased investor, insurer, and credit rating agency attention to climate risk and the associated financial impacts or cost of capital for borrowers vulnerable to climate risk.[304,305] More publicly traded companies are estimating and disclosing the financial impacts of climate change and the investments made to reduce climate-related risks and to maximize the opportunities.[306] These evolutions may cause a shift in perspective by private investors if investment returns are perceived to be at risk from climate change.

- **Unsupportive legal and regulatory environment:** Although there are examples of regulatory mandates for adaptation planning (e.g., California Public Utilities Commission Rulemaking R.18-04-019[307] and New York State Senate Bill 7802[308]), in many contexts, the legal and regulatory institutions and infrastructure that support adaptation investment are insufficient, either because they are themselves underfunded (KM 31.3) or because political support is lacking (or both). Insufficient, weak, or nonexistent regulatory and policy frameworks (e.g., lack of or delayed adoption of forward-looking infrastructure codes and standards; KM 12.3) create barriers to action and investment. Such policy decisions limit incentives to address physical climate risk and reduce the likelihood of mobilization of finance.

# Traceable Accounts

## *Process Description*

Adaptation to climate change has the potential to affect people from all walks of life, so the author team was selected to represent people from a diverse range of disciplines including social sciences and engineering, as well as professional practitioners focused on adaptation. Care was taken to ensure that the team included both early-career and senior professionals from across industry, academia, and government who come from varying geographic areas and personal backgrounds. The authors were selected from the list of individuals who responded to the Federal Register Notice or otherwise directly contacted the US Global Change Research Program to volunteer. Authors met virtually on a weekly or bi-weekly basis throughout the assessment to build consensus, incorporate feedback from stakeholders received during the public workshops and comment periods, and collaborate and cross-reference other Fifth National Climate Assessment chapters where relevant.

It is important to note that while the terms "adaptation" and "resilience" are complementary concepts, there are distinct and important differences between the meanings of these terms, and confusion arises since they are often used interchangeably in policy and academic discourse. "At its most basic, adaptation refers to a process or action that changes a living thing so that it is better able to survive in a new environment, whereas resilience describes the capacity or ability to anticipate and cope with shocks, and to recover from their impacts in a timely and efficient manner. However, in practice, the distinctions and relationships between resilience and adaptation are more complicated and less easily defined."[309]

Historically, resilience was referenced as "bouncing back" and involved a return to baselines—such as a community recovering to its pre-disaster state after an acute climate-related event, such as an earthquake or hurricane.[310] More recently, however, the disaster planning and adaptation communities have realized that "bouncing back" to the status quo can be harmful. Therefore, the term "resilience" has recently been discussed as "bouncing forward"—changing a system or community to be better prepared for future conditions, whether those are sudden shocks like hurricanes or long-term stressors like drought and sea level rise. Bouncing forward implies that there has been reflection, growth, and learning, which does not always occur and is not always captured and evaluated after shocks and stresses have occurred. There are also communities that are forced to be resilient and can either bounce forward or bounce back depending on their access to the resources and support that meet their specific needs in both the short and long term. This chapter focuses on actions that help communities "bounce forward" to prepare for and thrive under future conditions.

## Key Message 31.1

## Adaptation Is Occurring but Is Insufficient in Relation to the Pace of Climate Change

### Description of Evidence Base

The state of climate adaptation in the US has been somewhat well-documented through literature and organizations capturing publicly available adaptation actions to date at multiple scales, such as the Georgetown Climate Center, the Intergovernmental Panel on Climate change,[150] the Global Adaptation Mapping Initiative,[15] and this National Climate Assessment. In addition, there are numerous studies documenting diverse barriers to adaptation, including psychological, regulatory, financial, and political barriers.[43,44,45,48] The chapter authors, as adaptation practitioners and researchers, understand in depth the current state

of adaptation and progress—or lack thereof—being made across the US from the local to the national scale and wove that into the evidence base. The authors were able to capture evidence of progress and barriers along the various stages of the adaptation cycle from recent research and literature, public comments, and their professional experience. Although there is progress being made across the US, there are still significant barriers to overcome for Americans to adapt to climate change now and into the future. The chapter documents these barriers further in the Key Message narrative and highlights some on-the-ground examples to illustrate these barriers.

### Major Uncertainties and Research Gaps

Given the lack of research on evaluating the effectiveness and sufficiency of adaptation actions across multiple sectors, scales, and regions, the authors focused on evaluating the current status of and barriers to adaptation across the five stages of the adaptation cycle. Authors felt as though the previous graphics[4,19] that illustrate progress along the adaptation cycle do not accurately reflect the varying levels of progress from the national to local scale. For example, a rural town in Kansas may be at the awareness stage, whereas the City of New York is in between the implementation and monitoring and evaluation stages of the cycle. Given this disparity in the level of progress along the cycle, authors included examples—captured from literature and author experience—of progress and barriers to each stage of the adaptation cycle.

### Description of Confidence and Likelihood

*Very high confidence* in the diversity of adaptation actions occurring across the US stems from widespread and well-documented academic and policy reports about adaptation. While there are few documented examples of fully implemented adaptations, a lack of systematic studies of adaptation implementation that enable a comparison over time and the difficulty of comparing across regions and sectors yield *medium confidence* that adaptation is moving from the planning to implementation phase. Available research agrees that few implemented adaptations are being evaluated (*high confidence*) and that organizations face numerous barriers to developing and implementing adaptations (*high confidence*). Most available sources agree that current adaptation efforts and investments are incremental in nature and are insufficient to address future climate risks (*high confidence*). However, projecting and evaluating actual levels of risk reduction remains difficult, which leads to our statement of *medium confidence* related to current adaptation efforts and investments being unlikely to keep pace with future changes in the climate.

There is no consistent or regularly updated and tracked source for adaptation actions across the US at multiple scales, regions, or sectors, and many actions that may be considered adaptation may not be publicly known or captured through sources currently available that do track adaptation actions (e.g., the Intergovernmental Panel on Climate Change [IPCC] and the Georgetown Climate Center [GCC]). Therefore, the chapter's authors can provide confidence levels but not likelihood assessments.

## Key Message 31.2

## Effective Adaptation Requires Centering Equity

### Description of Evidence Base

A substantial number of peer-reviewed papers, government data and reports, and accounts from extreme weather and climate events illustrate the uneven effects of climate change (Chs. 16, 18, 20).[62,63,64,65,66] Specifically, there is mounting evidence of the ways climate change disproportionately impacts low-income communities with higher percentages of Black, Indigenous, and Latin people, women, and younger or older adult populations, among others. Research and government reports document numerous ways in which government and private-sector systems contribute to differential effects through discrimination, displace-

ment, or underinvestment in hazard mitigation, other public infrastructure, or disaster response (e.g., Frank 2020;[69] Wilson et al. 2021;[70] Howell and Elliott 2019[68]). Some disparities are better documented than others, but the finding that climate change affects populations differently and that some of these differences are driven by government (in)actions and social systems is not disputed in the literature.

There is a converging body of evidence that demonstrates that individual and social factors play a significant role in whether people have the resources to reduce or avoid climate impacts (e.g., adaptation), as is the case in other areas of society (e.g., access to education as a limiting factor to job security).[84,85,86,87] The specific reasons why individuals and communities adapt the way they do remains an area for research, but there is robust evidence and high consensus that psychological, cultural, historical, geographical, and social factors play a role and that individual or community values are important drivers in the adaptation process.[95,96,311,312]

Maladaptation is a well-established concept in the adaptation literature, and cases of maladaptation have been well documented in numerous cases by a range of author teams,[106,107] although the exact criteria used to determine when an action is maladaptive often differ according to context. A growing body of research documents the ways that centering equity in the design, planning, and implementation stages of adaptation leads to improved outcomes.[40,113,117]

### Major Uncertainties and Research Gaps

A source of uncertainty is the lack of standardized methods to evaluate the social justice or equity implications of climate adaptation. Numerous studies have documented inequities and injustices in adaptation or hazard risk-reduction programs and actions (e.g., Frank 2020;[69] Wilson et al. 2021;[70] Howell and Elliott 2019[68]), but different author teams use different metrics and concepts, including participatory, distributive, or recognition justice. The different methods make comparative analyses challenging, although notably the many methods and teams reach similar conclusions about the desirability of centering equity and justice to both improve quality of life for affected communities and reduce climate-related risks.

### Description of Confidence and Likelihood

There is strong evidence from a wide range of academic studies and government reports, with high levels of agreement across numerous research teams, that people are affected by climate change in different ways and to different degrees and that these differences are affected by historical and contemporary social systems. This statement therefore warranted *very high confidence*. Similarly, there is widespread, robust evidence with strong consensus that adaptation choices are influenced by preferences, capacity, and access to resources as well as personal and community values, so this statement was also considered to have *very high confidence*. The statement that adaptation actions that do not center equity and underlying causes of injustice can exacerbate inequity and increase climate risk is considered *high confidence* because there is widespread consensus about this claim, but the evidence is slightly less robust due to a lack of standardized methods to assess the social justice of adaptation outcomes. Studies documenting maladaptation when equity is not centered also bolster this conclusion.

## Key Message 31.3

## Transformative Adaptation Will Be Needed to Adequately Address Climate-Related Risks

### Description of Evidence Base

There is a significant and robust literature documenting the occurrence and type of adaptation practices globally and in the United States.[15] Technical contributors to this chapter reviewed adaptation actions as

documented in government reports and adaptation plans, as collected by the GCC Adaptation Clearinghouse and a systematic review. Researchers use several frameworks to assess transformative adaptation actions, but core principles relate to the depth or novelty of the change, the scale of the change (e.g., geographic or across multiple sectors), and the ability to address fundamental traits of systems or to challenge constraints of adaptation.[40,90,122,123] The IPCC Sixth Assessment Report, Working Group 2, for example, reviewed the relative frequency of incremental and transformative adaptation in over 1,800 studies using a modified version of the Termeer et al. (2017)[123] framework.[150]

Determining whether transformative adaptation is necessary in a particular case or whether incremental adaptation is sufficient for a given location or sector requires evaluation of not only individual adaptation actions but also suites of actions. Adaptation actions are difficult to evaluate, as the goals of adaptation are often contested, and the effectiveness or sufficiency of actions may not become apparent for a long time[16,313,314] (see discussion below in "Major Uncertainties and Research Gaps"). Nevertheless, a common finding within the literature is that most adaptation actions are incremental, small in scale, and limited by soft and hard constraints on adaptation.[1,15] Studies that assess the sufficiency of adaptation actions to address future climate change impacts routinely find that current incremental actions may be insufficient,[27,120] where sufficiency is determined based on projected climate change effects and limitations of adaptation actions (e.g., the ability of irrigation systems to handle future droughts). While the degree to which future actions will need to be transformative is uncertain (e.g., whether some, most, or all actions will need to be transformative), the literature supports *high confidence* that more actions will need to be transformative in the future than is current practice. That is, the US adaptation portfolio will need to include more transformative adaptation to adequately address future climate risks.

## Major Uncertainties and Research Gaps

The major source of uncertainty is a lack of consistent, high-quality methods to evaluate the sufficiency of adaptation actions to address future climate-related risks. Methods are being developed (e.g., Parker et al. 2020[27]), but lack of consistency across the field makes comparative studies difficult and complicates efforts to pin down optimal adaptation portfolios. Methods for decision-making under uncertainty are growing for this reason, as are methods to identify actions and portfolios of actions that are robust under numerous climate futures. Efforts to evaluate both the effectiveness of adaptation actions and portfolios in addressing current climate-related risks and the sufficiency of actions and portfolios to address future climate risks are areas for continuing research.

## Description of Confidence and Likelihood

There is *very high confidence* that climate adaptation actions in the United States to date have been incremental, because numerous information sources reporting adaptation actions in academic and government literature document these results and generally agree on the incremental nature of the adaptation actions. Although there is evidence of a few examples of transformative action, the overall statement that actions are generally small in scale and incremental remains robustly supported with strong evidence and high consensus. The necessity of transformative adaptation is assigned *high confidence* because numerous author teams and government reports reach this conclusion, but there is less robust evidence to support the extent of transformation that will be necessary. Similarly, numerous research teams conclude that monitoring and evaluation of adaptation will need to improve, both in terms of the methods used and the data collection and processes, to better understand what adaptation actions are effective to deal with current risks or sufficient to address future climate risks. However, not all teams agree on the nature of these monitoring and evaluation methods, so the need for improvement is assigned *high confidence*. The finding that adaptation actions in the United States (both the type and extent of actions) are generally insufficient to deal with future climate risks is not controversial in the literature. Likelihood

statements were not provided because they represent probabilistic assessments of uncertainty that are inappropriate for this type of analysis.

## Key Message 31.4

## Effective Adaptation Governance Empowers Multiple Voices to Navigate Competing Goals

### Description of Evidence Base

Research on adaptation governance and how adaptation decisions are made is a less developed topic relative to research on mitigation policy and governance,[156,158] especially for papers empirically focused on the US. Over the last five years, an increasing number of case studies have focused on adaptation governance in specific locations and sectors, such as sea level rise in San Francisco[159] or flood risk in the Upper Mississippi basin.[48] Existing case studies of adaptation governance display a high level of agreement with respect to its multi-actor, fragmented nature, wherein actors working in distinct organizations and sectors make independent decisions related to adaptation in an uncoordinated fashion.[48,49,50,159,165,166] This literature also highlights that these organizations have distinct goals, values, risk perceptions, and capabilities that lead to inconsistent and sometimes conflicting adaptation choices.[160,161,162,163,164] Both theoretical and empirical literature on adaptation governance also emphasize the benefits of increased coordination and collaboration across organizations, sectors, and levels of government.[1,51,165,172,173]

### Major Uncertainties and Research Gaps

The major source of uncertainty is a lack of systematic, cross-case research comparing adaptation governance approaches across multiple sectors, types of adaptation, or geographies. The majority of evidence stems from single case studies or comparisons of two or three city or community cases. The lack of larger comparative studies creates uncertainty about the specific contexts in which governance approaches work and more universal challenges in implementation. Comparative research has assessed the use of specific policy tools to promote adaptation[315,316] but rarely focuses on broader governance arrangements, such as who is involved in decision-making and the roles they play (an exception is Fastiggi et al. 2021[165]). Likewise, there is minimal research evaluating the outcomes of governance approaches on adoption of adaptation actions, risk reduction, or equity.

### Description of Confidence and Likelihood

*High confidence* about the diversity of actors involved in adaptation governance and the challenge of balancing competing goals signals that these statements rely on many high-quality papers that show the same general trends. *Medium confidence* about the need for collaboration and diversity of values and knowledge signals that there is a lower overall number of papers showing empirically the value of these approaches.

## Key Message 31.5

## Adaptation Requires More Than Scientific Information and Understanding

### Description of Evidence Base

Many integrated, science-based approaches are used to help manage decisions under uncertainty and decisions spanning future social–economic–environmental futures.[162,163,210] Even though some future uncer-

tainties cannot be reduced (Ch. 18) for particular strategies, many other strategies can take advantage of computing power and artificial intelligence to reduce future uncertainty, hedge against uncertainty by selecting actions that work across multiple possible futures, or approach adaptation decisions as a long-term process to be revisited over time.[195,235,317,318,319,320,321,322,323,324,325,326,327,328,329,330,331,332,333,334,335] Tools include modifications to traditional approaches like cost–benefit analysis, scenario planning, and multicriteria decision analysis; more participatory versions such as participatory mapping and serious gaming;[240,244] computational methods such as robust decision-making, probabilistic decisions, and real-options analysis; less computationally intense options such as heuristics, a growing area of research; and flexible options such as dynamic adaptation policy pathways[235] and adaptive management and governance systems.

A wealth of peer-reviewed literature over at least the past two decades provides formal and informal evaluation of specific climate service efforts and examines the use of climate information for a variety of decision-making contexts and applications. Recent research in this body of literature made strides by illustrating that equally important to whether climate information is used is how climate information is used. Specifically, it is important to acknowledge that any one specific climate service effort need not change a specific policy or real-world condition to benefit progress toward those or other outcomes.

Climate services can have numerous societal benefits and support diverse outcomes (see, for example, the Pacific Islands Regional Climate Assessment Evaluation[336]).[246,248] Over the past two decades, social science has improved the development of climate services by evaluating the usability of services,[337] prescriptively improving public data products,[338,339] and, more recently, expanding the degree to which various service efforts support adaptation and related societal benefits. Social science, including formal and informal evaluation of climate services, has improved our ability to generate usable and actionable climate information.[151,228,247,337,340] Additionally, social and behavioral science illustrate that actionable climate information can be complemented with new models of participatory, adaptive decision-making geared toward long-term behavior change.[162,231,232,234,337,341,342,343,344,345,346,347]

While the aforementioned literature evaluating climate services speaks to trust, legitimacy, and other important indications that dimensions of equity (e.g., procedural) may or may not have been achieved in different climate service efforts, the body of research only recently has started to examine equity as a critical component of climate services, as an intentional or deliberate part of both the evaluation and the climate service effort itself. Furthermore, equity in adaptation is a relatively new area of literature, and efforts to link the two bodies of work may also be limited by ambiguity over the definition of what constitutes a climate service. Additionally, attribution remains a thorny problem for evaluation research and investigations into the use of climate information, as well as for equity in adaptation. More work will be needed to determine the relative influence of a climate service effort alone versus the combination of a climate service effort and preexisting community organizing efforts to make a difference in catalyzing equitable adaptation. Nevertheless, of the climate service efforts proven to have a range of societal impacts leading to positive social and environmental outcomes and/or adaptive decisions, many have drawn on foundational work by Cash et al. (2003),[221] rooted in the concepts of legitimacy and saliency defined from a stakeholder perspective.

## Major Uncertainties and Research Gaps

Additional research would be beneficial to evaluate how well different models of climate service 1) align with different decision contexts, 2) contribute to societal benefits/impacts and outcomes, and 3) support dimensions of equity, particularly around racial and economic disparity. Spanning all three issues related to climate services, more research would be needed to more fully investigate the efficacy of various forms of engagement and collaborative decision-making and how they factor into coproduced climate services. More institutional research would also be needed to determine ways that for-profit services can generate value (e.g., empowerment, revenue) for lower-income communities.

### Description of Confidence and Likelihood

*High confidence* stems from a wealth of literature that climate services do provide a range of benefits and have met a range of needs. *Medium confidence* stems from less literature on equity in adaptation and climate services specifically, and, where that research exists, definitional ambiguity and problems with attribution of societal outcomes directly to climate services, as opposed to a combination of factors.

## Key Message 31.6

## Adaptation Investments and Financing Are Difficult to Track and May Be Inadequate

### Description of Evidence Base

The author team reviewed the literature by searching databases, inviting technical contributions from subject-matter experts, and soliciting feedback during public meetings.

Economic analysis of the costs and benefits of adaptation is a significant research field with numerous studies covering a range of sectors and geographies. Relevant studies include Melvin et al. (2017);[277] Reguero et al. (2018);[278] Martinich and Crimmins (2019);[273] Fant et al (2020);[128] Lorie et al. (2020);[281] Neumann et al. (2021);[274] Wobus et al. (2021);[279] LeRoy et al. (2019);[348] and Clavet et al. (2021).[349]

The peer-reviewed literature abounds with studies estimating the costs of adaptation, although these examples tend to coalesce around a subset of climate hazards, mostly flooding and other hydroclimate-related hazards (e.g., Clavet et al. 2021;[349] Lorie et al. 2020;[281] Melvin et al. 2017;[277] Neumann et al. 2021;[274] Reguero et al. 2018;[278] Wobus et al. 2021[279]); around a subset of sectors, historically agriculture, energy, and water; and in specific geographies, although there are several recent studies that evaluate the economics of adaptation for the continental US.[273,274,276,279] Time horizons for implementation of adaptation options vary across studies (e.g., next decades versus midcentury versus end of century), which can make it difficult to compare cost and benefit estimates. Recent studies (e.g., Neumann et al. 2021[274]) have attempted to incorporate estimation of the indirect costs of climate change on different sectors (e.g., train delays resulting from effects of temperature on rail lines) and these estimates' effect on evaluation of adaptation options.

Since the publication of the Fourth National Climate Assessment, there has been increased research into the effects of different adaptation implementation scenarios (e.g., proactive, reactive, and no adaptation) on damages associated with climate change (e.g., Martinich and Crimmins 2019;[273] Fant et al 2020;[128] Neumann et al 2021[274]), with much of this work supported by the EPA's Climate Change Impacts and Risk Analysis project.

Many organizations have climate investment tracking initiatives and publish regular reports on investment levels and flows (e.g., Climate Policy Initiative, World Bank, United Nations Environment Programme). This tracking is most robust at the international level and at monitoring investment and finance flows between countries, specifically transfers from developed nations to developing nations or transfers to international adaptation funding mechanisms.[284] Specific statistics on investment levels within countries, including the US, are more challenging to find. This is due in part to the fact that adaptation-related investments are not always labeled as such, especially when compared to climate change mitigation–related investments. Finally, tracking of public sector climate investment flows (e.g., from governments or multilateral institutions such as development banks) is also more robust than tracking of private-sector climate flows.

## Major Uncertainties and Research Gaps

Despite the multiple case studies of individual examples of adaptation, evidence is unclear about how coordinated or transformative these activities are. The lack of detailed information on adaptation-related investment does not indicate that it is not occurring but rather that it may be uneven, uncoordinated, or underreported. Thus, a major source of uncertainty in assessing the current state of adaptation is assessing the extent to which it is being adequately funded and financed in a coordinated way. Research gaps center on improved tracking of within-country and private-sector adaptation investments; identifying methods to track investment needs or levels when it is difficult to categorize adaptation-related investments; and developing improved metrics and methods for justifying adaptation-related investments.

More finance options have emerged to assist communities with covering the costs of adaptation. The chapter briefly cites four examples: the Louisiana's Strategic Adaptations for Future Environments, a fund administered by the State of Louisiana to provide community-driven adaptation support to residents, targeting the housing, transportation, and energy sectors; the DC Water's Environmental Impact Bond, an environmental impact bond to share with investors the financial performance risk associated with projects to respond to water stress facing the systems; investments from community development financial institutions, such as Coastal Enterprises Inc. in Maine; and a parametric insurance program for the Miami–Dade School District, developed by reinsurer Swiss Re. More research, specifically in the US, investigating the rates of uptake and share of different financing types utilized compared to others would be valuable.

## Description of Confidence and Likelihood

Multiple sources[275,284,290,291,295] consistently call out the lack of data on private-sector investments in adaptation, especially when compared to data on public-sector investments and financing. New et al. (2022)[284] note that progress has been made in tracking climate finance internationally but identify tracking of domestic public-sector and overall private-sector investments as critical gaps. For these reasons, there is *high confidence* that more investment in adaptation and improved tracking of domestic adaptation-related investments would be significantly beneficial.

Where adaptation may be occurring, the literature does cite evidence of underinvestment. Lorie et al. 2020[281] cite studies that reported that observed adaptation is lower than what would be expected from traditional cost–benefit analyses. There are many factors that influence the decision to adapt, including finances, lack of incentives, and technological unavailability, suggesting barriers to the decision to invest. Without a full picture of where adaptation investments are occurring and the nature of adaptation investments across sectors and communities, it is difficult to determine the adequacy of these investments. For these reasons, the authors decided to assign *medium confidence* to the statement that investments may be inadequate.

Studies that evaluate differences in aggregate costs of climate change across different scenarios consistently project higher economic costs under very high scenarios (e.g., RCP8.5) compared to intermediate (e.g., RCP4.5) or lower scenarios. Estimates of adaptation costs, which can translate into future investment needs, are consistently in the hundreds of millions to billions of dollars.[273,274,276,277,278,279] As many of these estimates are for specific sectors (as opposed to a comprehensive national-level assessment) and do not evaluate all possible climate impact pathways (for example, Fant et al. 2020[128] does not account for the impact of floods, hurricanes, and ice storms on transmission and distribution infrastructure), they may underestimate the total costs of climate change–related damages and total benefits of adaptation. For these reasons, there is *high confidence* that future investments needs will be significant but still substantial uncertainty as to what those figures will actually be.

Proactive adaptation has been shown to reduce costs compared to reactive and no adaptation scenarios,[128,274] with most benefits accruing in the later decades of the 21st century as warming levels increase under

high scenarios. The choice of discount rate influences the additional cost reductions of proactive adaptation relative to reactive adaptation. Because of this and the fact that analyses of the effects of different adaptation scenarios are limited to select sectors, there is *medium confidence* in this part of the Key Message.

Multiple examples of events in recent decades that have caused significant economic damages and loss of life suggest that communities are not well adapted to face current climate conditions, including ways in which current climate conditions have changed with global warming. Events such as the Texas winter storm in February 2021, where cold temperatures were extreme but not unprecedented in the historical record, demonstrate that many communities are unprepared for current climate conditions. Similarly, Wobus et al. (2021)[279] report that current flood-related risk is serious enough in many locations to justify adaptation-related investments now. For this reason, there is *high confidence* that adaptation is needed to address the risks posed by current climate conditions.

# References


1. Hicke, J.A., S. Lucatello, L.D. Mortsch, J. Dawson, M.D. Aguilar, C.A.F. Enquist, E.A. Gilmore, D.S. Gutzler, S. Harper, K. Holsman, E.B. Jewett, T.A. Kohler, and K. Miller, 2022: Ch. 14. North America. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1929–2042. https://doi.org/10.1017/9781009325844.016

2. Halofsky, J.E., D.L. Peterson, and R.A. Gravenmier, 2022: Climate Change Vulnerability and Adaptation in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest. Gen. Tech. Rep. PNW-GTR-1001. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 469 pp. https://doi.org/10.2737/pnw-gtr-1001

3. IPCC, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964

4. Lempert, R.J., J.R. Arnold, R.S. Pulwarty, K. Gordon, K. Greig, C. Hawkins-Hoffman, D. Sands, and C. Werrell, 2018: Ch. 28. Reducing risks through adaptation actions. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1309–1345. https://doi.org/10.7930/nca4.2018.ch28

5. National Academy of Sciences, 2020: *Climate Change: Evidence and Causes: Update 2020*. The National Academies Press, Washington, DC, 36 pp. https://doi.org/10.17226/25733

6. Keller, J., 2023: A Systems Approach to Climate Change Adaptation. WSP Global, accessed March 17, 2023. http://network.wsp-pb.com/article/a-systems-approach-to-climate-change-adaptation

7. Biagini, B., R. Bierbaum, M. Stults, S. Dobardzic, and S.M. McNeeley, 2014: A typology of adaptation actions: A global look at climate adaptation actions financed through the Global Environment Facility. *Global Environmental Change*, **25**, 97–108. https://doi.org/10.1016/j.gloenvcha.2014.01.003

8. GCC, 2022: State and Local Adaptation Plans. Georgetown University, Georgetown Climate Center. https://www.georgetownclimate.org/adaptation/plans.html

9. Castaño-Sánchez, J.P., H.D. Karsten, and C.A. Rotz, 2022: Double cropping and manure management mitigate the environmental impact of a dairy farm under present and future climate. *Agricultural Systems*, **196**, 103326. https://doi.org/10.1016/j.agsy.2021.103326.

10. d'Armengol, L., M.P. Castillo, I. Ruiz-Mallén, and E. Corbera, 2018: A systematic review of co-managed small-scale fisheries: Social diversity and adaptive management improve outcomes. *Global Environmental Change*, **52**, 212–225. https://doi.org/10.1016/j.gloenvcha.2018.07.009

11. Díaz, P., K.M. Morley, and D.H. Yeh, 2017: Resilient urban water supply: Preparing for the slow-moving consequences of climate change. *Water Practice and Technology*, **12**, 123–138. https://doi.org/10.2166/wpt.2017.016.

12. Ghahramani, A. and D. Bowran, 2018: Transformative and systemic climate change adaptations in mixed crop-livestock farming systems. *Agricultural Systems*, **164**, 236–251. https://doi.org/10.1016/j.agsy.2018.04.011.

13. Lamborn, C.C. and J.W. Smith, 2019: Human perceptions of, and adaptations to, shifting runoff cycles: A case-study of the Yellowstone River (Montana, USA). *Fisheries Research*, **216**, 96–108. https://doi.org/10.1016/j.fishres.2019.04.005.

14. Ontl, T.A., C. Swanston, L.A. Brandt, P.R. Butler, A.W. D'Amato, S.D. Handler, M.K. Janowiak, and P.D. Shannon, 2018: Adaptation pathways: Ecoregion and land ownership influences on climate adaptation decision-making in forest management. *Climatic Change*, **146** (1), 75–88. https://doi.org/10.1007/s10584-017-1983-3

15. Berrang-Ford, L., A.R. Siders, A. Lesnikowski, A.P. Fischer, M.W. Callaghan, et al., 2021: A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, **11** (11), 989–1000. https://doi.org/10.1038/s41558-021-01170-y

16. Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, **62**, 102071. https://doi.org/10.1016/j.gloenvcha.2020.102071

17. Poe, M.R., J. Donatuto, and T. Satterfield, 2016: "Sense of place": Human wellbeing considerations for ecological restoration in Puget Sound. *Coastal Management*, **44** (5), 409–426. https://doi.org/10.1080/08920753.2016.1208037

18. Singh, C., S. Iyer, M.G. New, R. Few, B. Kuchimanchi, A.C. Segnon, and D. Morchain, 2022: Interrogating 'effectiveness' in climate change adaptation: 11 guiding principles for adaptation research and practice. *Climate and Development*, **14** (7), 650–664. https://doi.org/10.1080/17565529.2021.1964937

19. Bierbaum, R., A. Lee, J. Smith, M. Blair, L.M. Carter, F.S. Chapin, III, P. Fleming, S. Ruffo, S. McNeeley, M. Stults, L. Verduzco, and E. Seyller, 2014: Ch. 28. Adaptation. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 670–706. https://doi.org/10.7930/j07h1ggt

20. Marlon, J.R., X. Wang, P. Bergquist, P.D. Howe, A. Leiserowitz, E. Maibach, M. Mildenberger, and S. Rosenthal, 2022: Change in US state-level public opinion about climate change: 2008–2020. *Environmental Research Letters*, **17** (12), 124046. https://doi.org/10.1088/1748-9326/aca702

21. Copeland, C., 2020: How North American companies are assessing environmental risk: 7 revealing findings. CDP. https://www.cdp.net/en/articles/companies/how-north-american-companies-are-assessing-environmental-risk-7-revealing-findings

22. Woodruff, S.C., 2022: Coordinating plans for climate adaptation. *Journal of Planning Education and Research*, **42** (2), 218–230. https://doi.org/10.1177/0739456x18810131

23. Kim, H., D.W. Marcouiller, and K.M. Woosnam, 2020: Coordinated planning effort as multilevel climate governance: Insights from coastal resilience and climate adaptation. *Geoforum*, **114**, 77–88. https://doi.org/10.1016/j.geoforum.2020.05.023

24. The White House, 2021: FACT SHEET: Biden administration releases agency climate adaptation and resilience plans from across Federal Government. The White House, Washington, DC, October 7, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/10/07/fact-sheet-biden-administration-releases-agency-climate-adaptation-and-resilience-plans-from-across-federal-government/

25. Gilmore, E.A. and T. St.Clair, 2018: Budgeting for climate change: Obstacles and opportunities at the US state level. *Climate Policy*, **18** (6), 729–741. https://doi.org/10.1080/14693062.2017.1366891

26. McGinn, A., 2023: Climate Adaptation: A Review of Federal Legislation Enacted Since 2017. Environmental and Energy Study Institute. https://www.eesi.org/articles/view/climate-adaptation-a-review-of-federal-legislation-enacted-since-2017

27. Parker, L.E., A.J. McElrone, S.M. Ostoja, and E.J. Forrestel, 2020: Extreme heat effects on perennial crops and strategies for sustaining future production. *Plant Science*, **295**, 110397. https://doi.org/10.1016/j.plantsci.2019.110397

28. Wheeler, K.G., B. Udall, J. Wang, E. Kuhn, H. Salehabadi, and J.C. Schmidt, 2022: What will it take to stabilize the Colorado River? *Science*, **377** (6604), 373–375. https://doi.org/10.1126/science.abo4452

29. Azhoni, A., S. Jude, and I. Holman, 2018: Adapting to climate change by water management organisations: Enablers and barriers. *Journal of Hydrology*, **559**, 736–748. https://doi.org/10.1016/j.jhydrol.2018.02.047

30. Dupuis, J. and R. Biesbroek, 2013: Comparing apples and oranges: The dependent variable problem in comparing and evaluating climate change adaptation policies. *Global Environmental Change*, **23** (6), 1476–1487. https://doi.org/10.1016/j.gloenvcha.2013.07.022

31. Eriksen, S., E.L.F. Schipper, M. Scoville-Simonds, K. Vincent, H.N. Adam, N. Brooks, B. Harding, D. Khatri, L. Lenaerts, D. Liverman, M. Mills-Novoa, M. Mosberg, S. Movik, B. Muok, A. Nightingale, H. Ojha, L. Sygna, M. Taylor, C. Vogel, and J.J. West, 2021: Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development*, **141**, 105383. https://doi.org/10.1016/j.worlddev.2020.105383

32. Kenney, M.A. and M.D. Gerst, 2021: Synthesis of indicators, datasets, and frameworks available to establish resilience and adaptation indicators: Case study of Chesapeake Bay region, USA. *Current Climate Change Reports*, **7** (2), 35–44. https://doi.org/10.1007/s40641-021-00170-6

33. Moser, S.C., J. Coffee, and A. Seville, 2017: Rising to the Challenge, Together: A Review and Critical Assessment of the State of the US Climate Adaptation Field. The Kresge Foundation, Troy, MI. https://kresge.org/content/rising-challenge-together

34. Onofri, L. and P.A.L.D. Nunes, 2020: Economic valuation for policy support in the context of ecosystem-based adaptation to climate change: An indicator, integrated based approach. *Heliyon*, **6** (8), e04650. https://doi.org/10.1016/j.heliyon.2020.e04650

35. Johnson, F.A., M.J. Eaton, G. McMahon, R. Nilius, M.R. Bryant, D.J. Case, J. Martin, N.J. Wood, and L. Taylor, 2015: Global change and conservation triage on National Wildlife Refuges. *Ecology and Society*, **20** (4). https://doi.org/10.5751/ES-07986-200414

36. Nalau, J. and B. Verrall, 2021: Mapping the evolution and current trends in climate change adaptation science. *Climate Risk Management*, **32**, 100290. https://doi.org/10.1016/j.crm.2021.100290

37. Sietsma, A.J., J.D. Ford, M.W. Callaghan, and J.C. Minx, 2021: Progress in climate change adaptation research. *Environmental Research Letters*, **16**, 054038. https://doi.org/10.1088/1748-9326/abf7f3

38. Klein, R.J.T., G.F. Midgley, B.L. Preston, M. Alam, F.G.H. Berkhout, K. Dow, and M.R. Shaw, 2014: Ch. 16. Adaptation opportunities, constraints, and limits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 899–943. https://www.ipcc.ch/report/ar5/wg2/

39. Thomas, A., E. Theokritoff, A. Lesnikowski, D. Reckien, K. Jagannathan, R. Cremades, D. Campbell, E.T. Joe, A. Sitati, C. Singh, A.C. Segnon, B. Pentz, J.I. Musah-Surugu, C.A. Mullin, K.J. Mach, L. Gichuki, E. Galappaththi, V.I. Chalastani, I. Ajibade, R. Ruiz-Diaz, C. Grady, M. Garschagen, J. Ford, K. Bowen, and T. Global Adaptation Mapping Initiative, 2021: Global evidence of constraints and limits to human adaptation. *Regional Environmental Change*, **21** (3), 85. https://doi.org/10.1007/s10113-021-01808-9

40. Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372** (6549), 8054. https://doi.org/10.1126/science.abc8054

41. Shi, L., S. Ahmad, P. Shukla, and S. Yupho, 2021: Shared injustice, splintered solidarity: Water governance across urban-rural divides. *Global Environmental Change*, **70**, 102354. https://doi.org/10.1016/j.gloenvcha.2021.102354

42. Green, K.M., J.C. Selgrath, T.H. Frawley, W.K. Oestreich, E.J. Mansfield, J. Urteaga, S.S. Swanson, F.N. Santana, S.J. Green, J. Naggea, and L.B. Crowder, 2021: How adaptive capacity shapes the Adapt, React, Cope response to climate impacts: Insights from small-scale fisheries. *Climatic Change*, **164** (1), 15. https://doi.org/10.1007/s10584-021-02965-w

43. Klasic, M., A. Fencl, J.A. Ekstrom, and A. Ford, 2022: Adapting to extreme events: Small drinking water system manager perspectives on the 2012–2016 California drought. *Climatic Change*, **170** (3), 26. https://doi.org/10.1007/s10584-021-03305-8

44. Rasmussen, D.J., R.E. Kopp, R. Shwom, and M. Oppenheimer, 2021: The political complexity of coastal flood risk reduction: Lessons for climate adaptation public works in the U.S. *Earth's Future*, **9** (2), e2020EF001575. https://doi.org/10.1029/2020ef001575

45. Ulibarri, N., K.A. Goodrich, P. Wagle, M. Brand, R. Matthew, E.D. Stein, and B.F. Sanders, 2020: Barriers and opportunities for beneficial reuse of sediment to support coastal resilience. *Ocean & Coastal Management*, **195**, 105287. https://doi.org/10.1016/j.ocecoaman.2020.105287

46. Arribas, A., R. Fairgrieve, T. Dhu, J. Bell, R. Cornforth, G. Gooley, C.J. Hilson, A. Luers, T.G. Shepherd, R. Street, and N. Wood, 2022: Climate risk assessment needs urgent improvement. *Nature Communications*, **13** (1), 4326. https://doi.org/10.1038/s41467-022-31979-w

47. OSTP, 2023: A Federal Framework and Action Plan for Climate Services. White House Office of Science and Technology Policy. https://www.whitehouse.gov/wp-content/uploads/2023/03/ftac_report_03222023_508.pdf

48. Reed, T., L.R. Mason, and C.C. Ekenga, 2020: Adapting to climate change in the Upper Mississippi River Basin: Exploring stakeholder perspectives on river system management and flood risk reduction. *Environmental Health Insights*, **14**, 1178630220984153. https://doi.org/10.1177/1178630220984153

49. Brush, L. and A. Bailey, 2021: A Federal Policy Action Plan to Accelerate Local Climate Resilience. Center for Climate and Energy Solutions. https://www.c2es.org/wp-content/uploads/2021/10/a-federal-policy-action-plan-to-accelerate-local-climate-resilience.pdf

50. Fields, B. and J.L. Renne, 2021: Ch. 9. South Florida and Miami: Rising seas and a fragmented response. In: *Adaptation Urbanism and Resilient Communities: Transforming Streets to Address Climate Change*. Routledge, 153–166. https://doi.org/10.4324/9780429026805

51. Fried, H., M. Hamilton, and R. Berardo, 2022: Closing integrative gaps in complex environmental governance systems. *Ecology and Society*, **27** (1). https://doi.org/10.5751/es-12996-270115

52. Haggerty, J.H., M.N. Haggerty, K. Roemer, and J. Rose, 2018: Planning for the local impacts of coal facility closure: Emerging strategies in the U.S. West. *Resources Policy*, **57**, 69–80. https://doi.org/10.1016/j.resourpol.2018.01.010

53. Morris, A.C., 2016: The Challenge of State Reliance on Revenue from Fossil Fuel Production. Climate and Energy Economics Discussion Paper. The Brookings Institution, Washington, DC. https://www.brookings.edu/wp-content/uploads/2016/08/state-fiscal-implications-of-fossil-fuel-production-0809216-morris.pdf

54. Roemer, K.F. and J.H. Haggerty, 2022: The energy transition as fiscal rupture: Public services and resilience pathways in a coal company town. *Energy Research & Social Science*, **91**, 102752. https://doi.org/10.1016/j.erss.2022.102752

55. Araos, M., K. Jagannathan, R. Shukla, I. Ajibade, E. Coughlan de Perez, K. Davis, J.D. Ford, E.K. Galappaththi, C. Grady, A.J. Hudson, E.T. Joe, C.J. Kirchhoff, A. Lesnikowski, G.N. Alverio, M. Nielsen, B. Orlove, B. Pentz, D. Reckien, A.R. Siders, N. Ulibarri, M. van Aalst, T.Z. Abu, T. Agrawal, L. Berrang-Ford, R.B. Kerr, S. Coggins, M. Garschagen, A. Harden, K.J. Mach, A.M. Nunbogu, P. Spandan, S. Templeman, and L.L. Turek-Hankins, 2021: Equity in human adaptation-related responses: A systematic global review. *One Earth*, **4** (10), 1454–1467. https://doi.org/10.1016/j.oneear.2021.09.001

56. Foster, S., R. Leichenko, K.H. Nguyen, R. Blake, H. Kunreuther, M. Madajewicz, E.P. Petkova, R. Zimmerman, C. Corbin-Mark, E. Yeampierre, A. Tovar, C. Herrera, and D. Ravenborg, 2019: New York City Panel on Climate Change 2019 Report Chapter 6: Community-based assessments of adaptation and equity. *Annals of the New York Academy of Sciences*, **1439** (1), 126–173. https://doi.org/10.1111/nyas.14009

57. Adhikari, B. and L.S. Safaee Chalkasra, 2021: Mobilizing private sector investment for climate action: Enhancing ambition and scaling up implementation. *Journal of Sustainable Finance & Investment*, 1–18. https://doi.org/10.1080/20430795.2021.1917929

58. Ford, J.D., T. Pearce, G. McDowell, L. Berrang-Ford, J.S. Sayles, and E. Belfer, 2018: Vulnerability and its discontents: The past, present, and future of climate change vulnerability research. *Climatic Change*, **151** (2), 189–203. https://doi.org/10.1007/s10584-018-2304-1

59. Elliott, J.R. and J. Howell, 2017: Beyond disasters: A longitudinal analysis of natural hazards' unequal impacts on residential instability. *Social Forces*, **95** (3), 1181–1207. https://doi.org/10.1093/sf/sow086

60. Hardy, R.D. and M.E. Hauer, 2018: Social vulnerability projections improve sea-level rise risk assessments. *Applied Geography*, **91**, 10–20. https://doi.org/10.1016/j.apgeog.2017.12.019

61. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

62. Chakraborty, J., T.W. Collins, and S.E. Grineski, 2019: Exploring the environmental justice implications of Hurricane Harvey flooding in Greater Houston, Texas. *American Journal of Public Health*, **109**, 244–250. https://doi.org/10.2105/ajph.2018.304846

63. Davies, I.P., R.D. Haugo, J.C. Robertson, and P.S. Levin, 2018: The unequal vulnerability of communities of color to wildfire. *PLoS ONE*, **13** (11), 0205825. https://doi.org/10.1371/journal.pone.0205825

64. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

65. Messager, M.L., A.K. Ettinger, M. Murphy-Williams, and P.S. Levin, 2021: Fine-scale assessment of inequities in inland flood vulnerability. *Applied Geography*, **133**, 102492. https://doi.org/10.1016/j.apgeog.2021.102492

66. Tate, E., M.A. Rahman, C.T. Emrich, and C.C. Sampson, 2021: Flood exposure and social vulnerability in the United States. *Natural Hazards*, **106** (1), 435–457. https://doi.org/10.1007/s11069-020-04470-2

67. UAFINE, 2019: Statewide Threat Assessment: Identification of Threats from Erosion, Flooding, and Thawing Permafrost in Remote Alaska Communities. Report #INE 19.03. University of Alaska Fairbanks, Institute of Northern Engineering. https://www.denali.gov/wp-content/uploads/2019/11/Statewide-Threat-Assessment-Final-Report-20-November-2019.pdf

68. Howell, J. and J.R. Elliot, 2019: Damages done: The longitudinal impacts of natural hazards on wealth inequality in the United States. *Social Problems*, **66** (3), 448–467. https://doi.org/10.1093/socpro/spy016

69. Frank, T., 2020: Disaster loans entrench disparities in Black communities. *E&E News*, July 2, 2020. https://www.scientificamerican.com/article/disaster-loans-entrench-disparities-in-black-communities/

70. Wilson, B., E. Tate, and C.T. Emrich, 2021: Flood recovery outcomes and disaster assistance barriers for vulnerable populations. *Frontiers in Water*, **3**, 752307. https://doi.org/10.3389/frwa.2021.752307

71. Elliott, J.R., P.L. Brown, and K. Loughran, 2020: Racial inequities in the federal buyout of flood-prone homes: A nationwide assessment of environmental adaptation. *Socius*, **6**, 2378023120905439. https://doi.org/10.1177/2378023120905439

72. Marino, E., 2018: Adaptation privilege and voluntary buyouts: Perspectives on ethnocentrism in sea level rise relocation and retreat policies in the US. *Global Environmental Change*, **49**, 10–13. https://doi.org/10.1016/j.gloenvcha.2018.01.002

73. Siders, A.R., 2019: Managed retreat in the United States. *One Earth*, **1** (2), 216–225. https://doi.org/10.1016/j.oneear.2019.09.008

74. Malloy, J.T. and C.M. Ashcraft, 2020: A framework for implementing socially just climate adaptation. *Climatic Change*, **160**, 1–14. https://doi.org/10.1007/s10584-020-02705-6.

75. Bigger, P. and N. Millington, 2020: Getting soaked? Climate crisis, adaptation finance, and racialized austerity. *Environment and Planning E: Nature and Space*, **3** (3), 601–623. https://doi.org/10.1177/2514848619876539

76. Chen, T.H.Y. and B. Lee, 2022: Income-based inequality in post-disaster migration is lower in high resilience areas: Evidence from U.S. internal migration. *Environmental Research Letters*, **17** (3), 034043. https://doi.org/10.1088/1748-9326/ac5692

77. Medwinter, S.D., 2021: Reproducing poverty and inequality in disaster: Race, class, social capital, NGOs, and urban space in New York City after Superstorm Sandy. *Environmental Sociology*, **7**, 1–11. https://doi.org/10.1080/23251042.2020.1809054

78. Seong, K., C. Losey, and D. Gu, 2022: Naturally resilient to natural hazards? Urban–rural disparities in Hazard Mitigation Grant Program assistance. *Housing Policy Debate*, **32**, 190–210. https://doi.org/10.1080/10511482.2021.1938172

79. Lamba-Nieves, D. and R. Santiago-Bartolomei, 2022: Who gets emergency housing relief? An analysis of FEMA individual assistance data after Hurricane María. *Housing Policy Debate*, **33** (5), 1146–1166. https://doi.org/10.1080/10511482.2022.2055612

80. Méndez, M., G. Flores-Haro, and L. Zucker, 2020: The (in)visible victims of disaster: Understanding the vulnerability of undocumented Latino/a and Indigenous immigrants. *Geoforum*, **116**, 50–62. https://doi.org/10.1016/j.geoforum.2020.07.007

81. Domingue, S.J. and C.T. Emrich, 2019: Social vulnerability and procedural equity: Exploring the distribution of disaster aid across counties in the United States. *The American Review of Public Administration*, **49** (8), 897–913. https://doi.org/10.1177/0275074019856122

82. Meerow, S. and C.L. Mitchell, 2017: Weathering the storm: The politics of urban climate change adaptation planning. *Environment and Planning A: Economy and Space*, **49**, 2619–2627. https://doi.org/10.1177/0308518x17735225

83. Auer, M.R., 2021: Considering equity in wildfire protection. *Sustainability Science*, **16** (6), 2163–2169. https://doi.org/10.1007/s11625-021-01024-8

84. Hügel, S. and A.R. Davies, 2020: Public participation, engagement, and climate change adaptation: A review of the research literature. *WIREs Climate Change*, **11** (4). https://doi.org/10.1002/wcc.645

85. Mallette, A., T.F. Smith, C. Elrick-Barr, J. Blythe, and R. Plummer, 2021: Understanding preferences for coastal climate change adaptation: A systematic literature review. *Sustainability*, **13**, 8594. https://doi.org/10.3390/su13158594

86. Rittelmeyer, P., 2020: Socio-cultural perceptions of flood risk and management of a levee system: Applying the Q methodology in the California Delta. *Geoforum*, **111**, 11–23. https://doi.org/10.1016/j.geoforum.2020.02.022

87. Stephens, S.H., D.E. DeLorme, and S.C. Hagen, 2020: Coastal stakeholders' perceptions of sea level rise adaptation planning in the northern Gulf of Mexico. *Environmental Management*, **66**, 407–418. https://doi.org/10.1007/s00267-020-01315-3

88. Javeline, D., T. Kijewski-Correa, and A. Chesler, 2019: Does it matter if you "believe" in climate change? Not for coastal home vulnerability. *Climatic Change*, **155** (4), 511–532. https://doi.org/10.1007/s10584-019-02513-7

89. Rodríguez-Cruz, L.A. and M.T. Niles, 2021: Awareness of climate change's impacts and motivation to adapt are not enough to drive action: A look of Puerto Rican farmers after Hurricane Maria. *PLoS ONE*, **16** (1), e0244512. https://doi.org/10.1371/journal.pone.0244512

90. Fedele, G., C.I. Donatti, C.A. Harvey, L. Hannah, and D.G. Hole, 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, **101**, 116–125. https://doi.org/10.1016/j.envsci.2019.07.001

91. Garner, G., P. Reed, and K. Keller, 2016: Climate risk management requires explicit representation of societal trade-offs. *Climatic Change*, **134**, 713–723. https://doi.org/10.1007/s10584-016-1607-3

92. Tschakert, P., J. Barnett, N. Ellis, C. Lawrence, N. Tuana, M. New, C. Elrick-Barr, R. Pandit, and D. Pannell, 2017: Climate change and loss, as if people mattered: Values, places, and experiences. *WIREs Climate Change*, **8** (5), e476. https://doi.org/10.1002/wcc.476

93. Clarke, D., C. Murphy, and I. Lorenzoni, 2018: Place attachment, disruption and transformative adaptation. *Journal of Environmental Psychology*, **55**, 81–89. https://doi.org/10.1016/j.jenvp.2017.12.006

94. Jin, D., P. Hoagland, D.K. Au, and J. Qiu, 2015: Shoreline change, seawalls, and coastal property values. *Ocean & Coastal Management*, **114**, 185–193. https://doi.org/10.1016/j.ocecoaman.2015.06.025

95. Whyte, K., 2020: Too late for Indigenous climate justice: Ecological and relational tipping points. *WIREs Climate Change*, **11** (1), e603. https://doi.org/10.1002/wcc.603

96. Yarina, L., M. Mazereeuw, and L. Ovalles, 2019: A retreat critique: Deliberations on design and ethics in the flood zone. *Journal of Landscape Architecture*, **14** (3), 8–23. https://doi.org/10.1080/18626033.2019.1705570

97. Ghahramani, L., K. McArdle, and S. Fatorić, 2020: Minority community resilience and cultural heritage preservation: A case study of the Gullah Geechee community. *Sustainability*, **12** (6). https://doi.org/10.3390/su12062266

98. Barnett, J. and S.J. O'Neill, 2013: Ch. 7. Minimising the risk of maladaptation: A framework for analysis. In: *Climate Adaptation Futures*. Palutikof, J., S.L. Boulter, A.J. Ash, M.S. Smith, M. Parry, M. Waschka, and D. Guitart, Eds. Wiley, 87–93. https://doi.org/10.1002/9781118529577.ch7

99. Basche, A., K. Tully, N.L. Álvarez-Berríos, J. Reyes, L. Lengnick, T. Brown, J.M. Moore, R.E. Schattman, L.K. Johnson, and G. Roesch-McNally, 2020: Evaluating the untapped potential of US conservation investments to improve soil and environmental health. *Frontiers in Sustainable Food Systems*, **4**, 547876. https://doi.org/10.3389/fsufs.2020.547876

100. Walthall, C., P. Backlund, J. Hatfield, L. Lengnick, E. Marshall, M. Walsh, S. Adkins, M. Aillery, E.A. Ainsworth, C. Amman, C.J. Anderson, I. Bartomeus, L.H. Baumgard, F. Booker, B. Bradley, D.M. Blumenthal, J. Bunce, K. Burkey, S.M. Dabney, J.A. Delgado, J. Dukes, A. Funk, K. Garrett, M. Glenn, D.A. Grantz, D. Goodrich, S. Hu, R.C. Izaurralde, R.A.C. Jones, S.-H. Kim, A.D.B. Leaky, K. Lewers, T.L. Mader, A. McClung, J. Morgan, D.J. Muth, M. Nearing, D.M. Oosterhuis, D. Ort, C. Parmesan, W.T. Pettigrew, W. Polley, R. Rader, C. Rice, M. Rivington, E. Rosskopf, W.A. Salas, L.E. Sollenberger, R. Srygley, C. Stöckle, E.S. Takle, D. Timlin, J.W. White, R. Winfree, L. Wright-Morton, and L.H. Ziska, 2012: Climate Change and Agriculture in the United States: Effects and Adaptation. USDA Technical Bulletin 1935. U.S. Department of Agriculture, Washington, DC, 186 pp. https://www.usda.gov/sites/default/files/documents/CC%20and%20Agriculture%20Report%20(02-04-2013)b.pdf

101. Breen, M.J., A.S. Kebede, and C.S. König, 2022: The safe development paradox in flood risk management: A critical review. *Sustainability*, **14** (24), 16955. https://doi.org/10.3390/su142416955

102. Hutton, N.S., G.A. Tobin, and B.E. Montz, 2019: The levee effect revisited: Processes and policies enabling development in Yuba County, California. *Journal of Flood Risk Management*, **12** (3), 12469. https://doi.org/10.1111/jfr3.12469

103. Logan, T., S. Guikema, and J. Bricker, 2018: Hard-adaptive measures can increase vulnerability to storm surge and tsunami hazards over time. *Nature Sustainability*, **1** (9), 526–530. https://doi.org/10.1038/s41893-018-0137-6

104. Cutter, S.L., 2018: Compound, cascading, or complex disasters: What's in a name? *Environment: Science and Policy for Sustainable Development*, **60** (6), 16–25. https://doi.org/10.1080/00139157.2018.1517518

105. de Ruiter, M.C., A. Couasnon, M.J.C. van den Homberg, J.E. Daniell, J.C. Gill, and P.J. Ward, 2020: Why we can no longer ignore consecutive disasters. *Earth's Future*, **8** (3), e2019EF001425. https://doi.org/10.1029/2019ef001425

106. Atteridge, A. and E. Remling, 2018: Is adaptation reducing vulnerability or redistributing it? *WIREs Climate Change*, **9** (1), e500. https://doi.org/10.1002/wcc.500.

107. Bertana, A., B. Clark, T.M. Benney, and C. Quackenbush, 2022: Beyond maladaptation: Structural barriers to successful adaptation. *Environmental Sociology*, **8** (4), 448–458. https://doi.org/10.1080/23251042.2022.2068224

108. Siders, A.R., 2022: Navigating the middle space—Just transitions for U.S. coastal adaptation. *Shore & Beach*, **90** (4), 14–17. https://doi.org/10.34237/1009042

109. Dolšak, N. and A. Prakash, 2018: The politics of climate change adaptation. *Annual Review of Environment and Resources*, **43**, 317–341. https://doi.org/10.1146/annurev-environ-102017-025739

110. Doorn, N., L. Brackel, and S. Vermeulen, 2021: Distributing responsibilities for climate adaptation: Examples from the water domain. *Sustainability*, **13** (7), 3676. https://doi.org/10.3390/su13073676

111. Amorim-Maia, A.T., I. Anguelovski, E. Chu, and J. Connolly, 2022: Intersectional climate justice: A conceptual pathway for bridging adaptation planning, transformative action, and social equity. *Urban Climate*, **41**, 101053. https://doi.org/10.1016/j.uclim.2021.101053

112. Resurrección, B.P., B.A. Bee, I. Dankelman, C.M.Y. Park, M. Haldar, and C.P. McMullen, 2019: Gender-Transformative Climate Change Adaptation: Advancing Social Equity. Background paper to the 2019 report of the Global Commission on Adaptation. Stockholm Environment Institute, Rotterdam, Netherlands and Washington, DC, USA. https://www.sei.org/publications/gender-transformative-climate-change-adaptation-advancing-social-equity/

113. Pelling, M. and M. Garschagen, 2019: Put equity first in climate adaptation. *Nature*, **569** (7756), 327–329. https://doi.org/10.1038/d41586-019-01497-9

114. Schlosberg, D. and L.B. Collins, 2014: From environmental to climate justice: Climate change and the discourse of environmental justice. *WIREs Climate Change*, **5** (3), 359–374. https://doi.org/10.1002/wcc.275

115. van den Berg, H.J. and J.M. Keenan, 2019: Dynamic vulnerability in the pursuit of just adaptation processes: A Boston case study. *Environmental Science & Policy*, **94**, 90–100. https://doi.org/10.1016/j.envsci.2018.12.015

116. Whyte, K., 2011: The recognition dimensions of environmental justice in Indian Country. *Environmental Justice*, **4** (4), 185–186. https://doi.org/10.1089/env.2011.4401

117. Chu, E.K. and C.E.B. Cannon, 2021: Equity, inclusion, and justice as criteria for decision-making on climate adaptation in cities. *Current Opinion in Environmental Sustainability*, **51**, 85–94. https://doi.org/10.1016/j.cosust.2021.02.009

118. Executive Office of the President, 2021: Executive Order 14008: Tackling the climate crisis at home and abroad. *Federal Register*, **86** (19), 7619–7633. https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad

119. Young, S.D., B. Mallory, and A. Zaidi, 2023: Memorandum for the Heads of Executive Departments and Agencies: Addendum to the Interim Implementation Guidance for the Justice40 Initiative, M-21-28, on Using the Climate and Economic Justice Screening Tool (CEJST). Executive Office of the President, Washington, DC, 3 pp. https://www.whitehouse.gov/wp-content/uploads/2023/01/m-23-09_signed_ceq_cpo.pdf

120. Pinsky, M.L. and M. Fogarty, 2012: Lagged social–ecological responses to climate and range shifts in fisheries. *Climatic Change*, **115** (3–4), 883–891. https://doi.org/10.1007/s10584-012-0599-x

121. Brown, T.C., V. Mahat, and J.A. Ramirez, 2019: Adaptation to future water shortages in the United States caused by population growth and climate change. *Earth's Future*, **7** (3), 219–234. https://doi.org/10.1029/2018ef001091

122. Few, R., D. Morchain, D. Spear, A. Mensah, and R. Bendapudi, 2017: Transformation, adaptation and development: Relating concepts to practice. *Palgrave Communications*, **3** (1), 17092. https://doi.org/10.1057/palcomms.2017.92

123. Termeer, C.J.A.M., A. Dewulf, and G.R. Biesbroek, 2017: Transformational change: Governance interventions for climate change adaptation from a continuous change perspective. *Journal of Environmental Planning and Management*, **60** (4), 558–576. https://doi.org/10.1080/09640568.2016.1168288

124. Turek-Hankins, L.L., E. Coughlan de Perez, G. Scarpa, R. Ruiz-Diaz, P.N. Schwerdtle, E.T. Joe, E.K. Galappaththi, E.M. French, S.E. Austin, C. Singh, M. Siña, A.R. Siders, M.K. van Aalst, S. Templeman, A.M. Nunbogu, L. Berrang-Ford, T. Agrawal, The Global Adaptation Mapping Initiative Team, and K.J. Mach, 2021: Climate change adaptation to extreme heat: A global systematic review of implemented action. *Oxford Open Climate Change*, **1** (1). https://doi.org/10.1093/oxfclm/kgab005

125. Samuelson, W. and R. Zeckhauser, 1988: Status quo bias in decision making. *Journal of Risk and Uncertainty*, **1** (1), 7–59. https://doi.org/10.1007/bf00055564

126. Béné, C., A. Newsham, M. Davies, M. Ulrichs, and R. Godfrey-Wood, 2014: Review article: Resilience, poverty and development. *Journal of International Development*, **26** (5), 598–623. https://doi.org/10.1002/jid.2992

127. Carman, J.P. and M.T. Zint, 2020: Defining and classifying personal and household climate change adaptation behaviors. *Global Environmental Change*, **61**, 102062. https://doi.org/10.1016/j.gloenvcha.2020.102062

128. Fant, C., B. Boehlert, K. Strzepek, P. Larsen, A. White, S. Gulati, Y. Li, and J. Martinich, 2020: Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure. *Energy*, **195**, 116899. https://doi.org/10.1016/j.energy.2020.116899

129. McDonald, K.S., A.J. Hobday, P.A. Thompson, A. Lenton, R.L. Stephenson, B.D. Mapstone, L.X.C. Dutra, C. Bessey, F. Boschetti, C. Cvitanovic, C.M. Bulman, E.A. Fulton, C.H. Moeseneder, H. Pethybridge, E.E. Plagányi, E.I. van Putten, and P.C. Rothlisberg, 2019: Proactive, reactive, and inactive pathways for scientists in a changing world. *Earth's Future*, **7** (2), 60–73. https://doi.org/10.1029/2018ef000990

130. Miao, Q., M.K. Feeney, F. Zhang, E.W. Welch, and P.S. Sriraj, 2018: Through the storm: Transit agency management in response to climate change. *Transportation Research Part D: Transport and Environment*, **63**, 421–432. https://doi.org/10.1016/j.trd.2018.06.005

131. Gourevitch, J.D., R.M. Diehl, B.C. Wemple, and T.H. Ricketts, 2022: Inequities in the distribution of flood risk under floodplain restoration and climate change scenarios. *People and Nature*, **4** (2), 415–427. https://doi.org/10.1002/pan3.10290

132. Parton, L.C. and S.J. Dundas, 2020: Fall in the sea, eventually? A green paradox in climate adaptation for coastal housing markets. *Journal of Environmental Economics and Management*, **104**, 102381. https://doi.org/10.1016/j.jeem.2020.102381

133. Lenton, T.M., 2020: Tipping positive change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190123. https://doi.org/10.1098/rstb.2019.0123

134. Otto, I.M., J.F. Donges, R. Cremades, A. Bhowmik, R.J. Hewitt, W. Lucht, J. Rockström, F. Allerberger, M. McCaffrey, S.S.P. Doe, A. Lenferna, N. Morán, D.P. van Vuuren, and H.J. Schellnhuber, 2020: Social tipping dynamics for stabilizing Earth's climate by 2050. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (5), 2354–2365. https://doi.org/10.1073/pnas.1900577117

135. Tàbara, D.J., N. Frantzeskaki, K. Hölscher, S. Pedde, K. Kok, F. Lamperti, J.H. Christensen, J. Jäger, and P. Berry, 2018: Positive tipping points in a rapidly warming world. *Current Opinion in Environmental Sustainability*, **31**, 120–129. https://doi.org/10.1016/j.cosust.2018.01.012

136. Kates, R.W., W.R. Travis, and T.J. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (19), 7156–7161. https://doi.org/10.1073/pnas.1115521109

137. Siders, A.R., I. Ajibade, and D. Casagrande, 2021: Transformative potential of managed retreat as climate adaptation. *Current Opinion in Environmental Sustainability*, **50**, 272–280. https://doi.org/10.1016/j.cosust.2021.06.007

138. Rosenzweig, C., C. Mbow, L.G. Barioni, T.G. Benton, M. Herrero, M. Krishnapillai, E.T. Liwenga, P. Pradhan, M.G. Rivera-Ferre, T. Sapkota, F.N. Tubiello, Y. Xu, E. Mencos Contreras, and J. Portugal-Pereira, 2020: Climate change responses benefit from a global food system approach. *Nature Food*, **1** (2), 94–97. https://doi.org/10.1038/s43016-020-0031-z

139. Ajibade, I. and E.A. Adams, 2019: Planning principles and assessment of transformational adaptation: Towards a refined ethical approach. *Climate and Development*, **11**, 850–862. https://doi.org/10.1080/17565529.2019.1580557

140. Blythe, J., J. Silver, L. Evans, D. Armitage, N. Bennett, M.L. Moore, T. Morrison, and K. Brown, 2018: The dark side of transformation: Latent risks in contemporary sustainability discourse. *Antipode*, **50** (5), 1206–1223. https://doi.org/10.1111/anti.12405

141. Climate Justice Alliance, n.d.: Just Transition: A Framework for Change [Website], accessed May 23, 2023. https://climatejusticealliance.org/just-transition/

142. Dzebo, A., F. Lager, and R. Klein, 2022: Just Transition for Climate Adaptation: A Business Brief. Stockholm Environment Institute, Sweden. https://policycommons.net/artifacts/3184272/just-transition-for-climate-adaptation/3982892/

143. Kuhl, L., 2021: Policy making under scarcity: Reflections for designing socially just climate adaptation policy. *One Earth*, **4** (2), 202–212. https://doi.org/10.1016/j.oneear.2021.01.008

144. McNamara, D.E., S. Gopalakrishnan, M.D. Smith, and A.B. Murray, 2015: Climate adaptation and policy-induced inflation of coastal property value. *PLoS ONE*, **10** (3), e0121278. https://doi.org/10.1371/journal.pone.0121278

145. Shi, L. and A.M. Varuzzo, 2020: Surging seas, rising fiscal stress: Exploring municipal fiscal vulnerability to climate change. *Cities*, **100**, 102658. https://doi.org/10.1016/j.cities.2020.102658

146. Adler, D., M. Burger, R. Moore, and J. Scata, 2019: Changing the National Flood Insurance Program for a changing climate. *Environmental Law Reporter*, **49**, 10320. https://scholarship.law.columbia.edu/sabin_climate_change/65/

147. Craig, R.K., 2019: Coastal adaptation, government-subsidized insurance, and perverse incentives to stay. *Climatic Change*, **152** (2), 215–226. https://doi.org/10.1007/s10584-018-2203-5

148. Frazier, T., E.E. Boyden, and E. Wood, 2020: Socioeconomic implications of national flood insurance policy reform and flood insurance rate map revisions. *Natural Hazards*, **103** (1), 329–346. https://doi.org/10.1007/s11069-020-03990-1

149. Mechler, R., C. Singh, K. Ebi, R. Djalante, A. Thomas, R. James, P. Tschakert, M. Wewerinke-Singh, T. Schinko, D. Ley, J. Nalau, L.M. Bouwer, C. Huggel, S. Huq, J. Linnerooth-Bayer, S. Surminski, P. Pinho, R. Jones, E. Boyd, and A. Revi, 2020: Loss and damage and limits to adaptation: Recent IPCC insights and implications for climate science and policy. *Sustainability Science*, **15** (4), 1245–1251. https://doi.org/10.1007/s11625-020-00807-9

150. O'Neill, B., M. van Aalst, Z. Zaiton Ibrahim, L. Berrang Ford, S. Bhadwal, H. Buhaug, D. Diaz, K. Frieler, M. Garschagen, A. Magnan, G. Midgley, A. Mirzabaev, A. Thomas, and R. Warren, 2022: Ch. 16. Key risks across sectors and regions. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2411–2538. https://doi.org/10.1017/9781009325844.025

151. Arnott, J.C., S.C. Moser, and K.A. Goodrich, 2016: Evaluation that counts: A review of climate change adaptation indicators & metrics using lessons from effective evaluation and science-practice interaction. *Environmental Science & Policy*, **66**, 383–392. https://doi.org/10.1016/j.envsci.2016.06.017

152. Janetos, A.C., 2020: Why is climate adaptation so important? What are the needs for additional research? *Climatic Change*, **161**, 171–176. https://doi.org/10.1007/s10584-019-02651-y

153. Kenney, M.A. and A.C. Janetos, 2020: National indicators of climate changes, impacts, and vulnerability. *Climatic Change*, **163**, 1695–1704. https://doi.org/10.1007/s10584-020-02939-4.

154. Kenney, M.A., A.C. Janetos, and M.D. Gerst, 2020: A framework for national climate indicators. *Climatic Change*, **163** (4), 1705–1718. https://doi.org/10.1007/s10584-018-2307-y

155. Fisher, S. and A. Williams, 2020: Facing the Climate Crisis: Making the Bold and Ambitious Choices Needed for Transformational Change. A Transformational Change Learning Partnership Webinar. Climate Investment Funds. https://www.cif.org/knowledge-exchange/facing-climate-crisis-making-bold-and-ambitious-choices-needed-transformational

156. Huitema, D., W.N. Adger, F. Berkhout, E. Massey, D. Mazmanian, S. Munaretto, R. Plummer, and C.C.J.A.M. Termeer, 2016: The governance of adaptation: Choices, reasons, and effects. Introduction to the Special Feature. *Ecology and Society*, **21** (3), 37. https://doi.org/10.5751/es-08797-210337

157. Birchall, S.J. and N. Bonnett, 2021: Climate change adaptation policy and practice: The role of agents, institutions and systems. *Cities*, **108**, 103001. https://doi.org/10.1016/j.cities.2020.103001

158. Termeer, C., A. van Buuren, A. Dewulf, D. Huitema, H. Mees, S. Meijerink, and M. van Rijswick, 2017: *Governance Arrangements for Adaptation to Climate Change*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.600

159. Lubell, M. and M. Robbins, 2022: Adapting to sea-level rise: Centralization or decentralization in polycentric governance systems? *Policy Studies Journal*, **50** (1), 143–175. https://doi.org/10.1111/psj.12430

160. Lawrence, J., M. Haasnoot, and R. Lempert, 2020: Climate: Managing deep uncertainty. *Nature Correspondence*, **580**, 456–456. https://doi.org/10.3928/0098-9134-19830501-03

161. Molenveld, A., A. van Buuren, and G.-J. Ellen, 2020: Governance of climate adaptation, which mode? An exploration of stakeholder viewpoints on how to organize adaptation. *Climatic Change*, **162**, 233–254. https://doi.org/10.1007/s10584-020-02683-9

162. Orlove, B., R. Shwom, E. Markowitz, and S.-M. Cheong, 2020: Climate decision-making. *Annual Review of Environment and Resources*, **45** (1), 271–303. https://doi.org/10.1146/annurev-environ-012320-085130

163. Siders, A. and A.L. Pierce, 2021: Deciding how to make climate change adaptation decisions. *Current Opinion in Environmental Sustainability*, **52**, 1–8. https://doi.org/10.1016/j.cosust.2021.03.017

164. Stults, M. and L. Larsen, 2020: Tackling uncertainty in US local climate adaptation planning. *Journal of Planning Education and Research*, **40** (4), 416–431. https://doi.org/10.1177/0739456x18769134

165. Fastiggi, M., S. Meerow, and T.R. Miller, 2021: Governing urban resilience: Organisational structures and coordination strategies in 20 North American city governments. *Urban Studies*, **58** (6), 1262–1285. https://doi.org/10.1177/0042098020907277

166. Lubell, M., M. Stacey, and M.A. Hummel, 2021: Collective action problems and governance barriers to sea-level rise adaptation in San Francisco Bay. *Climatic Change*, **167** (3), 46. https://doi.org/10.1007/s10584-021-03162-5

167. Preston, B.L., E.J. Yuen, and R.M. Westaway, 2011: Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks. *Sustainability Science*, **6** (2), 177–202. https://doi.org/10.1007/s11625-011-0129-1

168. Revi, A., D.E. Satterthwaite, F. Aragón-Durand, J. Corfee-Morlot, R.B.R. Kiunsi, M. Pelling, D.C. Roberts, and W. Solecki, 2014: Ch. 8. Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 535–612. https://www.ipcc.ch/report/ar5/wg2/

169. Clavin, C.T., J. Helgeson, M. Malecha, and S. Shrivastava, 2023: A call for a National Community Resilience Extension Partnership to bridge resilience research to communities. *npj Urban Sustainability*, **3** (1), 21. https://doi.org/10.1038/s42949-023-00102-3

170. Moser, S.C. and L. Dilling, Eds., 2007: *Creating a Climate for Change: Communicating Climate Change and Facilitating Social Change*. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/cbo9780511535871

171. Moser, S.C. and A.L. Luers, 2008: Managing climate risks in California: The need to engage resource managers for successful adaptation to change. *Climatic Change*, **87** (S1), 309–322. https://doi.org/10.1007/s10584-007-9384-7

172. Bixler, R.P., K. Lieberknecht, S. Atshan, C.P. Zutz, S.M. Richter, and J.A. Belaire, 2020: Reframing urban governance for resilience implementation: The role of network closure and other insights from a network approach. *Cities*, **103**, 102726. https://doi.org/10.1016/j.cities.2020.102726

173. Plummer, R., 2013: Can adaptive comanagement help to address the challenges of climate change adaptation? *Ecology and Society*, **18** (4), 2. https://doi.org/10.5751/es-05699-180402

174. Altmann, G., n.d.: A Tribe's Collaborative Journey to Develop Forest Resiliency: A Story Map by Santa Clara Pueblo Forestry [Story Map]. Santa Clara Forestry Department, accessed September 6, 2022. https://www.arcgis.com/apps/Cascade/index.html?appid=23463ab7bf624b478e5553e27299d7e5

175. Biesbroek, G.R., R.J. Swart, T.R. Carter, C. Cowan, T. Henrichs, H. Mela, M.D. Morecroft, and D. Rey, 2010: Europe adapts to climate change: Comparing national adaptation strategies. *Global Environmental Change*, **20** (3), 440–450. https://doi.org/10.1016/j.gloenvcha.2010.03.005

176. Dickinson, T. and I. Burton, 2011: Ch. 7. Adaptation to climate change in Canada: A multi-level mosaic. In: *Climate Change Adaptation in Developed Nations*. Ford, J.D. and L. Berrang-Ford, Eds. Springer, Dordrecht, Netherlands, 103–117. https://doi.org/10.1007/978-94-007-0567-8_7

177. Smith, T.F., D.C. Thomsen, and N. Keys, 2011: Ch. 5. The Australian experience. In: *Climate Change Adaptation in Developed Nations*. Ford, J.D. and L. Berrang-Ford, Eds. Springer, Dordrecht, Netherlands, 69–84. https://doi.org/10.1007/978-94-007-0567-8_5

178. Zolnikov, T.R., K.P. Garces, K. Bolter, K. McGuigan, and R.K. King, 2020: Enhancing public health preparedness, response, and recovery capabilities through the Florida Hurricane Response Hub. *Climate Risk Management*, **30**, 100251. https://doi.org/10.1016/j.crm.2020.100251

179. Berrang-Ford, L., R. Biesbroek, J.D. Ford, A. Lesnikowski, A. Tanabe, F.M. Wang, C. Chen, A. Hsu, J.J. Hellmann, P. Pringle, M. Grecequet, J.C. Amado, S. Huq, S. Lwasa, and S.J. Heymann, 2019: Tracking global climate change adaptation among governments. *Nature Climate Change*, **9** (6), 440–449. https://doi.org/10.1038/s41558-019-0490-0

180. Sanchez-Rodriguez, R., 2009: Learning to adapt to climate change in urban areas. A review of recent contributions. *Current Opinion in Environmental Sustainability*, **1** (2), 201–206. https://doi.org/10.1016/j.cosust.2009.10.005

181. Coastal Zone Management Act of 1972. 92nd Congress, Pub. L. No. 92-583, 86 Stat. 1280–1289, October 27, 1972. https://www.congress.gov/92/statute/STATUTE-86/STATUTE-86-Pg1280.pdf

182. Pisor, A.C., X. Basurto, K.G. Douglass, K.J. Mach, E. Ready, J.M. Tylianakis, A. Hazel, M.A. Kline, K.L. Kramer, J.S. Lansing, M. Moritz, P.E. Smaldino, T.F. Thornton, and J.H. Jones, 2022: Effective climate change adaptation means supporting community autonomy. *Nature Climate Change*, **12** (3), 213–215. https://doi.org/10.1038/s41558-022-01303-x

183. Bryson, J.M., K.S. Quick, C.S. Slotterback, and B.C. Crosby, 2013: Designing public participation processes. *Public Administration Review*, **73** (1), 23–34. https://doi.org/10.1111/j.1540-6210.2012.02678.x

184. Johnston, E.W., D. Hicks, N. Nan, and J.C. Auer, 2011: Managing the inclusion process in collaborative governance. *Journal of Public Administration Research and Theory*, **21** (4), 699–721. https://doi.org/10.1093/jopart/muq045

185. Anderson, S.E., R.R. Bart, M.C. Kennedy, A.J. MacDonald, M.A. Moritz, A.J. Plantinga, C.L. Tague, and M. Wibbenmeyer, 2018: The dangers of disaster-driven responses to climate change. *Nature Climate Change*, **8** (8), 651–653. https://doi.org/10.1038/s41558-018-0208-8

186. PCAST, 2023: Extreme Weather Risk in a Changing Climate: Enhancing Prediction and Protecting Communities. Executive Office of the President, President's Council of Advisors on Science and Technology, Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2023/04/PCAST_Extreme-Weather-Report_April2023.pdf

187. GAO, 2021: Disaster Recovery: Efforts to Identify and Address Barriers to Receiving Federal Recovery Assistance. GAO-22-105488. U.S. Government Accountability Office. https://www.gao.gov/products/gao-22-105488

188. Tavares, A.O. and P.P. dos Santos, 2014: Re-scaling risk governance using local appraisal and community involvement. *Journal of Risk Research*, **17** (7), 923–949. https://doi.org/10.1080/13669877.2013.822915

189. United Cities and Local Governments, 2011: Local Government Finance: The Challenges of the 21st Century. Edward Elgar Publishing Limited, Cheltenham, UK. https://www.gold.uclg.org/sites/default/files/GOLD%20II_ENG.pdf

190. Rahman, H.M.T. and G.M. Hickey, 2019: What does autonomous adaptation to climate change have to teach public policy and planning about avoiding the risks of maladaptation in Bangladesh? *Frontiers in Environmental Science*, **7**, 2. https://doi.org/10.3389/fenvs.2019.00002

191. Birkmann, J., M. Garschagen, F. Kraas, and N. Quang, 2010: Adaptive urban governance: New challenges for the second generation of urban adaptation strategies to climate change. *Sustainability Science*, **5** (2), 185–206. https://doi.org/10.1007/s11625-010-0111-3

192. Gupta, J., C. Termeer, J. Klostermann, S. Meijerink, M. van den Brink, P. Jong, S. Nooteboom, and E. Bergsma, 2010: The adaptive capacity wheel: A method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environmental Science & Policy*, **13** (6), 459–471. https://doi.org/10.1016/j.envsci.2010.05.006

193. Driessen, P.P.J. and H.F.M.W. van Rijswick, 2011: Normative aspects of climate adaptation policies. *Climate Law*, **2** (4), 559–581. https://doi.org/10.1163/cl-2011-051

194. Chung Tiam Fook, T., 2017: Transformational processes for community-focused adaptation and social change: A synthesis. *Climate and Development*, **9** (1), 5–21. https://doi.org/10.1080/17565529.2015.1086294

195. Hallegatte, S., 2011: Ch. 10. Uncertainties in the cost-benefit analysis of adaptation measures, and consequences for decision making. In: *Climate Global Change and Local Adaptation*. Linkov, I. and T.S. Bridges, Eds. Springer, Dordrecht, Netherlands, 169–192. https://doi.org/10.1007/978-94-007-1770-1_10

196. Junod, A.N., C. Martín, R. Marx, and A. Rogin, 2021: Equitable Investments in Resilience: A Review of Benefit-Cost Analysis in Federal Flood Mitigation Infrastructure. Urban Institute. https://www.urban.org/sites/default/files/publication/104302/equitable-investments-in-resilience.pdf

197. Siders, A.R., 2019: Adaptive capacity to climate change: A synthesis of concepts, methods, and findings in a fragmented field. *WIREs Climate Change*, **10**, 573. https://doi.org/10.1002/wcc.573.

198. Guillén Bolaños, T., M. Máñez Costa, and U. Nehren, 2018: Ch. 10. Development of a prioritization tool for climate change adaptation measures in the forestry sector—A Nicaraguan case study. In: *Economic Tools and Methods for the Analysis of Global Change Impacts on Agriculture and Food Security*. Quiroga, S., Ed. Springer, Cham, Switzerland, 165–177. https://doi.org/10.1007/978-3-319-99462-8_10

199. Williams, D.S., L. Celliers, K. Unverzagt, N. Videira, M. Máñez Costa, and R. Giordano, 2020: A method for enhancing capacity of local governance for climate change adaptation. *Earth's Future*, **8** (7), e2020EF001506. https://doi.org/10.1029/2020ef001506

200. Setzer, J. and R. Byrnes, 2019: Global Trends in Climate Change Litigation: 2019 Snapshot. Grantham Research Institute on Climate Change and the Environment and London School of Economics and Political Science, Centre for Climate Change Economics and Policy, London, UK. https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2019/07/GRI_Global-trends-in-climate-change-litigation-2019-snapshot-2.pdf

201. Peel, J. and H.M. Osofsky, 2020: Climate change litigation. *Annual Review of Law and Social Science*, **16** (1), 21–38. https://doi.org/10.1146/annurev-lawsocsci-022420-122936

202. NYC Mayor's Office of Climate & Environmental Justice, 2022: Climate Resiliency Design Guidelines. City of New York. https://climate.cityofnewyork.us/initiatives/climate-resiliency-design-guidelines/

203. U.S. Federal Government, 2014: U.S. Climate Resilience Toolkit [Website]. http://toolkit.climate.gov

204. U.S. Federal Government, n.d.: Climate Mapping for Resilience and Adaptation [Website], accessed September 27, 2023. https://resilience.climate.gov/

205. NASA, n.d.: IPCC AR6 Sea Level Projection Tool. National Aeronautics and Space Administration, accessed September 27, 2023. https://sealevel.nasa.gov/data_tools/17

206. USGCRP, 2023: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023

207. Geospatial Innovation Facility at the University of California Berkeley, 2023: Cal-Adapt. State of California, California Energy Commission, accessed September 27, 2023. https://cal-adapt.org/

208. New York State Energy Research and Development Authority, 2020: New York Climate Change Science Clearinghouse. State of New York. https://data.ny.gov/Energy-Environment/New-York-Climate-Change-Science-Clearinghouse/tijd-2x34

209. New Mexico EMNRD, n.d.: New Mexico Climate Risk Map. New Mexico Energy, Minerals, and Natural Resources Department, accessed September 27, 2023. https://nmclimaterisk.org/

210. Shi, R., B.F. Hobbs, and H. Jiang, 2019: When can decision analysis improve climate adaptation planning? Two procedures to match analysis approaches with adaptation problems. *Climatic Change*, **157** (3), 611–630. https://doi.org/10.1007/s10584-019-02579-3

211. Dilling, L. and M.C. Lemos, 2011: Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environmental Change*, **21** (2), 680–689. https://doi.org/10.1016/j.gloenvcha.2010.11.006

212. Jacobs, K.L. and R.B. Street, 2020: The next generation of climate services. *Climate Services*, **20**, 100199. https://doi.org/10.1016/j.cliser.2020.100199

213. Kopp, R., 2021: Climate grant universities could mobilize community climate action. *Eos*, **102**. https://doi.org/10.1029/2021eo158178

214. Vaughan, C. and S. Dessai, 2014: Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews: Climate Change*, **5** (5), 587–603. https://doi.org/10.1002/wcc.290

215. DOT, 2023: Federal Interagency Thriving Communities Network. U.S. Department of Transportation. https://www.transportation.gov/federal-interagency-thriving-communities-network

216. FEMA, 2023: Direct Technical Assistance Communities. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/grants/mitigation/building-resilient-infrastructure-communities/direct-technical-assistance/communities

217. Moss, R., P.L. Scarlett, M.A. Kenney, H. Kunreuther, R. Lempert, J. Manning, B.K. Williams, J.W. Boyd, E.T. Cloyd, L. Kaatz, and L. Patton, 2014: Ch. 26. Decision support: Connecting science, risk perception, and decisions. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T. (T.C.) Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 620–647. https://doi.org/10.7930/j0h12zxg

218. Moss, R.H., S. Avery, K. Baja, M. Burkett, A.M. Chischilly, J. Dell, P.A. Fleming, K. Geil, K. Jacobs, A. Jones, K. Knowlton, J. Koh, M.C. Lemos, J. Melillo, R. Pandya, T.C. Richmond, L. Scarlett, J. Snyder, M. Stults, A.M. Waple, J. Whitehead, D. Zarrilli, B.M. Ayyub, J. Fox, A. Ganguly, L. Joppa, S. Julius, P. Kirshen, R. Kreutter, A. McGovern, R. Meyer, J. Neumann, W. Solecki, J. Smith, P. Tissot, G. Yohe, and R. Zimmerman, 2019: Evaluating knowledge to support climate action: A framework for sustained assessment. Report of an independent advisory committee on Applied Climate Assessment. *Weather, Climate, and Society*, **11** (3), 465–487. https://doi.org/10.1175/wcas-d-18-0134.1

219. Bednarek, A.T., C. Wyborn, C. Cvitanovic, R. Meyer, R.M. Colvin, P.F.E. Addison, S.L. Close, K. Curran, M. Farooque, E. Goldman, D. Hart, H. Mannix, B. McGreavy, A. Parris, S. Posner, C. Robinson, M. Ryan, and P. Leith, 2018: Boundary spanning at the science–policy interface: The practitioners' perspectives. *Sustainability Science*, **13** (4), 1175–1183. https://doi.org/10.1007/s11625-018-0550-9

220. Guston, D.H., 2001: Boundary organizations in environmental policy and science: An introduction. *Science, Technology, & Human Values*, **26** (4), 399–408. http://www.jstor.org/stable/690161

221. Cash, D.W., W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, D.H. Guston, J. Jäger, and R.B. Mitchell, 2003: Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America*, **100** (14), 8086–8091. https://doi.org/10.1073/pnas.1231332100

222. Clifford, K.R., W.R. Travis, and L.T. Nordgren, 2020: A climate knowledges approach to climate services. *Climate Services*, **18**, 100155. https://doi.org/10.1016/j.cliser.2020.100155

223. Kirchhoff, C.J., J.J. Barsugli, G.L. Galford, A.V. Karmalkar, K. Lombardo, S.R. Stephenson, M. Barlow, A. Seth, G. Wang, and A. Frank, 2019: Climate assessments for local action. *Bulletin of the American Meteorological Society*, **100** (11), 2147–2152. https://doi.org/10.1175/bams-d-18-0138.1

224. National Research Council, 2009: *Informing Decisions in a Changing Climate*. National Academies Press, Washington, DC, 200 pp. https://doi.org/10.17226/12626

225. Simpson, C.F., L. Dilling, K. Dow, K.J. Lackstrom, M.C. Lemos, and R.E. Riley, 2016: Ch. 1. Assessing needs and decision contexts: RISA approaches to engagement research. In: *Climate in Context: Science and Society Partnering for Adaptation*. Parris, A.S., G.M. Garfin, K. Dow, R. Meyer, and S.L. Close, Eds. Wiley, 3–26. https://doi.org/10.1002/9781118474785.ch1

226. Maldonado, J., T.M.B. Bennett, K. Chief, P. Cochran, K. Cozzetto, B. Gough, M.H. Redsteer, K. Lynn, N. Maynard, and G. Voggesser, 2016: Engagement with Indigenous Peoples and honoring traditional knowledge systems. *Climatic Change*, **135** (1), 111–126. https://doi.org/10.1007/s10584-015-1535-7

227. Chambers, J.M., C. Wyborn, N.L. Klenk, M. Ryan, A. Serban, N.J. Bennett, R. Brennan, L. Charli-Joseph, M.E. Fernández-Giménez, K.A. Galvin, B.E. Goldstein, T. Haller, R. Hill, C. Munera, J.L. Nel, H. Österblom, R.S. Reid, M. Riechers, M. Spierenburg, M. Tengö, E. Bennett, A. Brandeis, P. Chatterton, J.J. Cockburn, C. Cvitanovic, P. Dumrongrojwatthana, A. Paz Durán, J.-D. Gerber, J.M.H. Green, R. Gruby, A.M. Guerrero, A.-I. Horcea-Milcu, J. Montana, P. Steyaert, J.G. Zaehringer, A.T. Bednarek, K. Curran, S.J. Fada, J. Hutton, B. Leimona, T. Pickering, and R. Rondeau, 2022: Co-productive agility and four collaborative pathways to sustainability transformations. *Global Environmental Change*, **72**, 102422. https://doi.org/10.1016/j.gloenvcha.2021.102422

228. Finucane, M.L., M.J. Blum, R. Ramchand, A.M. Parker, S. Nataraj, N. Clancy, G. Cecchine, A. Chandra, T. Slack, G. Hobor, R.J. Ferreira, K. Luu, A.E. Lesen, and C.A. Bond, 2020: Advancing community resilience research and practice: Moving from "me" to "we" to "3D". *Journal of Risk Research*, **23** (1), 1–10. https://doi.org/10.1080/13669877.2018.1517377

229. Flagg, J.A. and C.J. Kirchhoff, 2018: Context matters: Context-related drivers of and barriers to climate information use. *Climate Risk Management*, **20**, 1–10. https://doi.org/10.1016/j.crm.2018.01.003

230. Gordon, E.S., L. Dilling, E. McNie, and A.J. Ray, 2016: Ch. 11. Navigating scales of knowledge and decision-making in the Intermountain West: Implications for science policy. In: *Climate in Context: Science and Society Partnering for Adaptation*. Parris, A.S., G.M. Garfin, K. Dow, R. Meyer, and S.L. Close, Eds. Wiley, 235–254. https://doi.org/10.1002/9781118474785.ch11

231. Dhami, S., A. Al-Nowaihi, and C.R. Sunstein, 2019: Heuristics and public policy: Decision-making under bounded rationality. *Studies in Microeconomics*, **7** (1), 7–58. https://doi.org/10.1177/2321022219832148

232. Gorddard, R., M.J. Colloff, R.M. Wise, D. Ware, and M. Dunlop, 2016: Values, rules and knowledge: Adaptation as change in the decision context. *Environmental Science & Policy*, **57**, 60–69. https://doi.org/10.1016/j.envsci.2015.12.004.

233. Rahmawati, P.I., M. Jiang, and T. DeLacy, 2019: Framework for stakeholder collaboration in harnessing corporate social responsibility implementation in tourist destination to build community adaptive capacity to climate change. *Corporate Social Responsibility and Environmental Management*, **26** (6), 1261–1271. https://doi.org/10.1002/csr.1745

234. Shannon, B.N., Z.A. McGee, and B.D. Jones, 2019: Bounded rationality and cognitive limits in political decision making. In: *Oxford Research Encyclopedia of Politics*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228637.013.961

235. Haasnoot, M., J.H. Kwakkel, W.E. Walker, and J. ter Maat, 2013: Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, **23** (2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

236. Linquiti, P. and N. Vonortas, 2012: The value of flexibility in adapting to climate change: A real options analysis of investments in coastal defense. *Climate Change Economics*, **3** (2), 1250008. https://doi.org/10.1142/s201000781250008x

237. Metzger, J., A. Carlsson Kanyama, P. Wikman-Svahn, K. Mossberg Sonnek, C. Carstens, M. Wester, and C. Wedebrand, 2021: The flexibility gamble: Challenges for mainstreaming flexible approaches to climate change adaptation. *Journal of Environmental Policy & Planning*, **23** (4), 543–558. https://doi.org/10.1080/1523908x.2021.1893160

238. Truong, C., S. Trück, and S. Mathew, 2018: Managing risks from climate impacted hazards – The value of investment flexibility under uncertainty. *European Journal of Operational Research*, **269** (1), 132–145. https://doi.org/10.1016/j.ejor.2017.07.012

239. Cintron-Rodriguez, I.M., H.A. Crim, D.L. Morrison, F. Niepold, J. Kretser, W. Spitzer, and T. Bowman, 2021: Equitable and empowering participatory policy design strategies to accelerate just climate action. *Journal of Science Policy & Governance*, **18** (2). https://doi.org/10.38126/jspg180203

240. Cravens, A.E., 2016: Negotiation and decision making with collaborative software: How MarineMap 'changed the game' in California's Marine Life Protected Act Initiative. *Environmental Management*, **57** (2), 474–497. https://doi.org/10.1007/s00267-015-0615-9

241. Cvitanovic, C., M. Howden, R.M. Colvin, A. Norström, A.M. Meadow, and P.F.E. Addison, 2019: Maximising the benefits of participatory climate adaptation research by understanding and managing the associated challenges and risks. *Environmental Science & Policy*, **94**, 20–31. https://doi.org/10.1016/j.envsci.2018.12.028

242. Flynn, M., J.D. Ford, T. Pearce, and S.L. Harper, 2018: Participatory scenario planning and climate change impacts, adaptation and vulnerability research in the Arctic. *Environmental Science & Policy*, **79**, 45–53. https://doi.org/10.1016/j.envsci.2017.10.012

243. Jeffers, J., 2020: Barriers to transformation towards participatory adaptation decision-making: Lessons from the Cork flood defences dispute. *Land Use Policy*, **90**, 104333. https://doi.org/10.1016/j.landusepol.2019.104333

244. Ulibarri, N., 2018: Collaborative model development increases trust in and use of scientific information in environmental decision-making. *Environmental Science & Policy*, **82**, 136–142. https://doi.org/10.1016/j.envsci.2018.01.022

245. Ferguson, D.B., M.L. Finucane, V.W. Keener, and G. Owen, 2016: Ch. 10. Evaluation to advance science policy: Lessons from Pacific RISA and CLIMAS. In: *Climate in Context: Science and Society Partnering for Adaptation*. Parris, A.S., G.M. Garfin, K. Dow, R. Meyer, and S.L. Close, Eds. Wiley, 215–234. https://doi.org/10.1002/9781118474785.ch10

246. Meadow, A.M. and G. Owen, 2021: Planning and Evaluating the Societal Impacts of Climate Change Research Projects: A Guidebook for Natural and Physical Scientists Looking to Make a Difference. University of Arizona, Tucson, AZ. https://doi.org/10.2458/10150.658313

247. Owen, G., D.B. Ferguson, and B. McMahan, 2019: Contextualizing climate science: Applying social learning systems theory to knowledge production, climate services, and use-inspired research. *Climatic Change*, **157**, 151–170. https://doi.org/10.1007/s10584-019-02466-x

248. Wall, T.U., A.M. Meadow, and A. Horganic, 2017: Developing evaluation indicators to improve the process of coproducing usable climate science. *Weather, Climate, and Society*, **9** (1), 95–107. https://doi.org/10.1175/wcas-d-16-0008.1

249. OSTP, NOAA, and FEMA, 2021: Opportunities for Expanding and Improving Climate Information and Services for the Public—A Report to the National Climate Task Force. White House Office of Science and Technology Policy, National Oceanic and Atmospheric Administration, and Federal Emergency Management Agency. https://www.globalchange.gov/browse/reports/opportunities-expanding-and-improving-climate-information-and-services-public

250. Tribal Adaptation Menu Team, 2019: Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu. Great Lakes Indian Fish and Wildlife Commission, Odanah, WI, 54 pp. https://forestadaptation.org/tribal-climate-adaptation-menu

251. EPA, 2023: Environmental Justice Grants, Funding and Technical Assistance. U.S. Environmental Protection Agency. https://www.epa.gov/environmentaljustice/environmental-justice-grants-funding-and-technical-assistance

252. Clancy, N., M.L. Finucane, J.R. Fischbach, D.G. Groves, D. Knopman, K.V. Patel, and L. Dixon, 2022: The Building Resilient Infrastructure and Communities Mitigation Grant Program: Incorporating Hazard Risk and Social Equity into Decisionmaking Processes. Homeland Security Operational Analysis Center operated by the RAND Corporation. https://doi.org/10.7249/rr-a1258-1

253. Ellam Yua, J. Raymond-Yakoubian, R. Aluaq Daniel, and C. Behe, 2022: A framework for co-production of knowledge in the context of Arctic research. *Ecology and Society*, **27** (1), 34. https://doi.org/10.5751/es-12960-270134

254. Matson, L., G.H.C. Ng, M. Dockry, M. Nyblade, H.J. King, M. Bellcourt, J. Bloomquist, P. Bunting, E. Chapman, D. Dalbotten, M.A. Davenport, K. Diver, M. Duquain, W. Graveen, K. Hagsten, K. Hedin, S. Howard, T. Howes, J. Johnson, S. Kesner, E. Kojola, R. LaBine, D.J. Larkin, M. Montano, S. Moore, A. Myrbo, M. Northbird, M. Porter, R. Robinson, C.M. Santelli, R. Schmitter, R. Shimek, N. Schuldt, A. Smart, D. Strong, J. Torgeson, D. Vogt, and A. Waheed, 2021: Transforming research and relationships through collaborative tribal-university partnerships on manoomin (wild rice). *Environmental Science & Policy*, **115**, 108–115. https://doi.org/10.1016/j.envsci.2020.10.010

255. McDermott, M., S. Mahanty, and K. Schreckenberg, 2013: Examining equity: A multidimensional framework for assessing equity in payments for ecosystem services. *Environmental Science & Policy*, **33**, 416–427. https://doi.org/10.1016/j.envsci.2012.10.006

256. Jagannathan, K., J.C. Arnott, C. Wyborn, N. Klenk, K.J. Mach, R.H. Moss, and K.D. Sjostrom, 2020: Great expectations? Reconciling the aspiration, outcome, and possibility of co-production. *Current Opinion in Environmental Sustainability*, **42**, 22–29. https://doi.org/10.1016/j.cosust.2019.11.010

257. Mach, K.J., M.C. Lemos, A.M. Meadow, C. Wyborn, N. Klenk, J.C. Arnott, N.M. Ardoin, C. Fieseler, R.H. Moss, L. Nichols, M. Stults, C. Vaughan, and G. Wong-Parodi, 2020: Actionable knowledge and the art of engagement. *Current Opinion in Environmental Sustainability*, **42**, 30–37. https://doi.org/10.1016/j.cosust.2020.01.002

258. Meadow, A.M., D.B. Ferguson, Z. Guido, A. Horangic, G. Owen, and T. Wall, 2015: Moving toward the deliberate coproduction of climate science knowledge. *Weather, Climate, and Society*, **7** (2), 179–191. https://doi.org/10.1175/wcas-d-14-00050.1

259. Community of Kotlik, J.S. Littell, N. Fresco, R.C. Toohey, and M. Chase, 2020: Looking Forward, Looking Back: Building Resilience Today Community Report. Aleutian Pribilof Islands Association, Kotlik and Fairbanks, AK, 48 pp. https://akcasc.org/wp-content/uploads/2021/03/Kotlik_Community-Report_1_19_21.pdf

260. Lemos, M.C., J.C. Arnott, N.M. Ardoin, K. Baja, A.T. Bednarek, A. Dewulf, C. Fieseler, K.A. Goodrich, K. Jagannathan, N. Klenk, K.J. Mach, A.M. Meadow, R. Meyer, R. Moss, L. Nichols, K.D. Sjostrom, M. Stults, E. Turnhout, C. Vaughan, G. Wong-Parodi, and C. Wyborn, 2018: To co-produce or not to co-produce. *Nature Sustainability*, **1** (12), 722–724. https://doi.org/10.1038/s41893-018-0191-0

261. City of New York, 2021: State of Climate Knowledge 2021. City of New York, 34 pp. https://www.nyc.gov/assets/orr/pdf/publications/CKE_Report.pdf

262. Clifford, K.R., J. Henderson, Z. McAlear, L. Dilling, B. Duncan, S. Ehert, S. Arens, R. Page, and U. Rick, 2023: The "nuts and bolts" of doing coproduction: Exploring implementation decisions in climate adaptation research with stakeholders. *Bulletin of the American Meteorological Society*, **104** (4), E872–E883. https://doi.org/10.1175/bams-d-21-0292.1

263. Moser, S.C. and J.A. Ekstrom, 2010: A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **107** (51), 22026–22031. https://doi.org/10.1073/pnas.1007887107

264. Hemming, V., A.E. Camaclang, M.S. Adams, M. Burgman, K. Carbeck, J. Carwardine, I. Chadès, L. Chalifour, S.J. Converse, L.N.K. Davidson, G.E. Garrard, R. Finn, J.R. Fleri, J. Huard, H.J. Mayfield, E.M. Madden, I. Naujokaitis-Lewis, H.P. Possingham, L. Rumpff, M.C. Runge, D. Stewart, V.J.D. Tulloch, T. Walshe, and T.G. Martin, 2022: An introduction to decision science for conservation. *Conservation Biology*, **36** (1), e13868. https://doi.org/10.1111/cobi.13868

265. Kenney, M.A., A.C. Janetos, and G.C. Lough, 2016: Building an integrated U.S. national climate indicators system. *Climatic Change*, **135** (1), 85–96. https://doi.org/10.1007/s10584-016-1609-1

266. Adger, W.N., 2006: Vulnerability. *Global Environmental Change*, **16** (3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

267. Cutter, S.L., B.J. Boruff, and W.L. Shirley, 2003: Social vulnerability to environmental hazards. *Social Science Quarterly*, **84** (2), 242–261. https://doi.org/10.1111/1540-6237.8402002

268. Khajehei, S., A. Ahmadalipour, W. Shao, and H. Moradkhani, 2020: A place-based assessment of flash flood hazard and vulnerability in the contiguous United States. *Scientific Reports*, **10** (1), 1–12. https://doi.org/10.1038/s41598-019-57349-z

269. Linkov, I. and B.D. Trump, 2019: *The Science and Practice of Resilience*. Springer, Cham, Switzerland, 209 pp. https://doi.org/10.1007/978-3-030-04565-4

270. Dillard, M. 2021: Inventory of Community Resilience Indicators & Assessment Frameworks. National Institute of Standards and Technology. https://doi.org/10.18434/mds2-2297

271. Gu, D., M. Dillard, M. Gerst, and J. Loerzel, 2023: Validating commonly used indicators for community resilience measurement. *Natural Hazards Review*, **24** (2), 04023008. https://doi.org/10.1061/NHREFO.NHENG-1642

272. Summers, A., C.H. Fletcher, D. Spirandelli, K. McDonald, J.-S. Over, T. Anderson, M. Barbee, and B.M. Romine, 2018: Failure to protect beaches under slowly rising sea level. *Climatic Change*, **151** (3), 427–443. https://doi.org/10.1007/s10584-018-2327-7

273. Martinich, J. and A. Crimmins, 2019: Climate damages and adaptation potential across diverse sectors of the United States. *Nature Climate Change*, **9** (5), 397–404. https://doi.org/10.1038/s41558-019-0444-6

274. Neumann, J.E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich, 2021: Climate effects on US infrastructure: The economics of adaptation for rail, roads, and coastal development. *Climatic Change*, **167** (3), 44. https://doi.org/10.1007/s10584-021-03179-w

275. UNEP, 2022: Adaptation Gap Report 2022: Too Little, Too Slow–Climate Adaptation Failure Puts World at Risk. United Nations Environment Programme, Nairobi, Kenya. https://www.unep.org/adaptation-gap-report-2022

276. Cohen, F., M. Glachant, and M. Söderberg, 2017: The Cost of Adapting to Climate Change: Evidence from the US Residential Sector. Grantham Research Institute on Climate Change and the Environment Working Paper No. 263; CCCEP Working Paper No. 297. Grantham Research Institute on Climate Change and the Environment, Centre for Climate Change Economics and Policy. https://www.lse.ac.uk/granthaminstitute/publication/the-cost-of-adapting-to-climate-change-evidence-from-the-us-residential-sector/

277. Melvin, A.M., P. Larsen, B. Boehlert, J.E. Neumann, P. Chinowsky, X. Espinet, J. Martinich, M.S. Baumann, L. Rennels, A. Bothner, D.J. Nicolsky, and S.S. Marchenko, 2017: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (2), E122–E131. https://doi.org/10.1073/pnas.1611056113

278. Reguero, B.G., M.W. Beck, D.N. Bresch, J. Calil, and I. Meliane, 2018: Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLoS ONE*, **13** (4), e0192132. https://doi.org/10.1371/journal.pone.0192132

279. Wobus, C., J. Porter, M. Lorie, J. Martinich, and R. Bash, 2021: Climate change, riverine flood risk and adaptation for the conterminous United States. *Environmental Research Letters*, **16** (9), 094034. https://doi.org/10.1088/1748-9326/ac1bd7

280. Multi-Hazard Mitigation Council, 2019: Natural Hazard Mitigation Saves: 2019 Report. National Institute of Building Sciences, Washington, DC. https://www.nibs.org/projects/natural-hazard-mitigation-saves-2019-report

281. Lorie, M., J.E. Neumann, M.C. Sarofim, R. Jones, R.M. Horton, R.E. Kopp, C. Fant, C. Wobus, J. Martinich, M. O'Grady, and L.E. Gentile, 2020: Modeling coastal flood risk and adaptation response under future climate conditions. *Climate Risk Management*, **29**, 100233. https://doi.org/10.1016/j.crm.2020.100233

282. Diaz, D. and F. Moore, 2017: Quantifying the economic risks of climate change. *Nature Climate Change*, **7**, 774–782. https://doi.org/10.1038/nclimate3411

283. Rose, S., D. Diaz, T. Carleton, L. Drouet, C. Guivarch, A. Méjean, and F. Piontek, 2022: Cross-working group box Economic in Ch. 16. Key risks across sectors and regions. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2411–2538. https://doi.org/10.1017/9781009325844.025

284. New, M., D. Reckien, D. Viner, C. Adler, S.-M. Cheong, C. Conde, A. Constable, E.C.d. Perez, A. Lammel, R. Mechler, B. Orlove, and W. Solecki, 2022: Ch. 17. Decision-making options for managing risk. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2539–2654. https://doi.org/10.1017/9781009325844.026

285. Rising, J.A., C. Taylor, M.C. Ives, and R.E.T. Ward, 2022: Challenges and innovations in the economic evaluation of the risks of climate change. *Ecological Economics*, **197**, 107437. https://doi.org/10.1016/j.ecolecon.2022.107437

286. Chambwera, M., G. Heal, C. Dubeux, S. Hallegatte, L. Leclerc, A. Markandya, B.A. McCarl, R. Mechler, and J.E. Neumann, 2014: Ch. 17. Economics of adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 945–977. https://www.ipcc.ch/report/ar5/wg2/

287. Gauthier, T., L.A. Hamilton, A. Bennett, K. McCormick, A. Perrault, J. Smith, S. Hoverter, J. Li, and J. Grannis, 2020: Equitable Adaptation Legal and Policy Toolkit. Georgetown Climate Center, Washington, DC. https://www.georgetownclimate.org/adaptation/toolkits/equitable-adaptation-toolkit/financing-funding-tools-paying-for-equitable-adaptation.html

288. Moser, S.C., J.A. Ekstrom, J. Kim, and S. Heitsch, 2019: Adaptation finance archetypes: Local governments' persistent challenges of funding adaptation to climate change and ways to overcome them. *Ecology and Society*, **24** (2), 28. https://doi.org/10.5751/es-10980-240228

289. UNFCCC, 2021: Fourth (2020) Biennial Assessment and Overview of Climate Finance Flows. United Nations Framework Convention on Climate Change, Bonn, Germany. https://unfccc.int/sites/default/files/resource/54307_1%20-%20UNFCCC%20BA%202020%20-%20Report%20-%20V4.pdf

290. Buchner, B., B. Naran, P. Fernandes, R. Padmanabhi, P. Rosane, M. Solomon, S. Stout, C. Strinati, R. Tolentino, G. Wakaba, Y. Zhu, C. Meattle, and S. Guzmán, 2021: Global Landscape of Climate Finance 2021. Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2021/

291. Naran, B., J. Connolly, P. Rosane, D. Wignarajah, E. Wakaba, and B. Buchner, 2022: Global Landscape of Climate Finance: A Decade of Data 2011–2020. Climate Policy Initiative. https://www.climatepolicyinitiative.org/wp-content/uploads/2022/10/Global-Landscape-of-Climate-Finance-A-Decade-of-Data.pdf

292. UNEP, 2021: Adaptation Gap Report 2021: The Gathering Storm–Adapting to Climate Change in a Post-Pandemic World. United Nations Environment Programme, Nairobi, Kenya. https://www.unep.org/resources/adaptation-gap-report-2021

293. ASAP, 2022: Ready-to-Fund Resilience. American Society of Adaptation Professionals. https://adaptationprofessionals.org/ready-to-fund-resilience/

294. Richmond, M. and K. Hallmeyer, 2019: Tracking Adaptation Finance: Advancing Methods to Capture Finance Flows in the Landscape. Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/tracking-adaptation-finance-advancing-methods-to-capture-finance-flows-in-the-landscape/

295. Dale, T.W., J. Gao, V.K. Avashia, S. Konrad, and A. Garg, 2021: Private Sector Adaptation Reporting as a Source of Input to the Global Stocktake. UNEP DTU Partnership and Indian Institute of Management Ahmedabad. https://backend.orbit.dtu.dk/ws/portalfiles/portal/265671362/private_sector_adaptation_in_the_global_stockake.pdf

296. LA SAFE, 2019: Louisiana's Strategic Adaptations for Future Environments [Website], accessed September 27, 2023. https://lasafe.la.gov/home/

297. EPA, 2017: DC Water's Environmental Impact Bond: A First of its Kind. U.S. Environmental Protection Agency, Water Infrastructure and Resiliency Finance Center, 5 pp. https://www.epa.gov/sites/default/files/2017-04/documents/dc_waters_environmental_impact_bond_a_first_of_its_kind_final2.pdf

298. CEI, 2019: 2018 Annual Report. Coastal Enterprises, Inc. https://www.ceimaine.org/about/annual-reports/

299. Community Disaster Resilience Zones Act of 2022. 117th Congress, Pub. L. No. 117-255, 136 Stat. 2363–2367, December 20, 2022. https://www.congress.gov/bill/117th-congress/senate-bill/3875/text

300. Robert T. Stafford Disaster Relief and Emergency Assistance Act. H.R.2707, 100th Congress, Pub. L. No. 100-707, November 23, 1988. https://www.congress.gov/bill/100th-congress/house-bill/2707

301. Leiter, T. and P. Pringle, 2018: Pitfalls and potential of measuring climate change adaptation through adaptation metrics. In: *Adaptation Metrics: Perspectives on Measuring, Aggregating and Comparing Adaptation Results*. Christiansen, L., G. Martinez, and P. Naswa, Eds. UNEP DTU Partnership, Copenhagen, Denmark, 29–47. https://resilientcities2018.iclei.org/wp-content/uploads/UDP_Perspectives-Adaptation-Metrics-WEB.pdf

302. Moser, S.C., J.A. Ekstrom, J. Kim, and S. Heitsch, 2018: Adaptation Finance Challenges: Characteristic Patterns Facing California Local Governments and Ways to Overcome Them. California's Fourth Climate Change Assessment. Publication Number: CCCA4-CNRA2018-007. California Natural Resources Agency. https://www.energy.ca.gov/sites/default/files/2019-12/governance_ccca4-cnra-2018-007_ada.pdf

303. Miller, A. and S. Swann, 2019: Driving Finance Today for the Climate Resilient Society of Tomorrow for the Global Commission on Adaptation. United Nations Environment Programme. https://www.unepfi.org/publications/driving-finance-today-for-the-climate-resilient-society-of-tomorrow/

304. Climate Finance Advisors, 2020: Understanding the Role of Climate Risk Transparency on Capital Pricing for Developing Countries. Policy Brief. Climate Finance Advisors Benefit LLC, Washington, DC. https://climatefinanceadvisors.com/wp-content/uploads/2020/10/FCDO-Report_PolicyBrief_11.25.2020.pdf

305. Moody's Investors Service, 2016: Climate Change and Sovereign Credit Risk. Moody's Investors Service, Inc. https://www.moodys.com/sites/products/productattachments/climate_trends_infographic_moodys.pdf

306. TCFD, 2021: Implementing the Recommendations of the Task Force on Climate-Related Financial Disclosures. Task Force on Climate-Related Financial Disclosures. https://assets.bbhub.io/company/sites/60/2021/07/2021-TCFD-Implementing_Guidance.pdf

307. CPUC, 2018: Order Instituting Rulemaking to Consider Strategies and Guidance for Climate Change Adaptation. Proceeding: R18-04-019. California Public Utilities Commission. https://docs.cpuc.ca.gov/searchres.aspx?docformat=all&docid=213511543

308. An Act to Amend the Public Service Law, in Relation to Storm Hardening and System Resiliency Plans. S.B. S7802, State of New York, January 11, 2022. https://www.nysenate.gov/legislation/bills/2021/s7802

309. Mehryar, S., 2022: What Is the Difference between Climate Change Adaptation and Resilience? The London School of Economics and Political Science, Grantham Research Institute. https://www.lse.ac.uk/granthaminstitute/explainers/what-is-the-difference-between-climate-change-adaptation-and-resilience/

310. Alexander, D.E., 2013: Resilience and disaster risk reduction: An etymological journey. *Natural Hazards and Earth System Sciences*, **13** (11), 2707–2716. https://doi.org/10.5194/nhess-13-2707-2013

311. Buchanan, M.K., M. Oppenheimer, and A. Parris, 2019: Values, bias, and stressors affect intentions to adapt to coastal flood risk: A case study from New York City. *Weather, Climate, and Society*, **11** (4), 809–821. https://doi.org/10.1175/WCAS-D-18-0082.1

312. Lau, J.D., A.M. Song, T. Morrison, M. Fabinyi, K. Brown, J. Blythe, E.H. Allison, and W.N. Adger, 2021: Morals and climate decision-making: Insights from social and behavioural sciences. *Current Opinion in Environmental Sustainability*, **52**, 27–35. https://doi.org/10.1016/j.cosust.2021.06.005

313. Morecroft, M.D., S. Duffield, M. Harley, J.W. Pearce-Higgins, N. Stevens, O. Watts, and J. Whitaker, 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science*, **366** (6471), 9256. https://doi.org/10.1126/science.aaw9256

314. Singh, C., J. Ford, D. Ley, A. Bazaz, and A. Revi, 2020: Assessing the feasibility of adaptation options: Methodological advancements and directions for climate adaptation research and practice. *Climatic Change*, **162** (2), 255–277. https://doi.org/10.1007/s10584-020-02762-x

315. Hughes, S., 2020: Principles, drivers, and policy tools for just climate change adaptation in legacy cities. *Environmental Science & Policy*, **111**, 35–41. https://doi.org/10.1016/j.envsci.2020.05.007

316. Ulibarri, N., I. Ajibade, E.K. Galappaththi, E.T. Joe, A. Lesnikowski, K.J. Mach, J.I. Musah-Surugu, G. Nagle Alverio, A.C. Segnon, A.R. Siders, G. Sotnik, D. Campbell, V.I. Chalastani, K. Jagannathan, V. Khavhagali, D. Reckien, Y. Shang, C. Singh, and Z. Zommers, 2022: A global assessment of policy tools to support climate adaptation. *Climate Policy*, **22** (1), 77–96. https://doi.org/10.1080/14693062.2021.2002251

317. Butler, J.R.A., A.M. Bergseng, E. Bohensky, S. Pedde, M. Aitkenhead, and R. Hamden, 2020: Adapting scenarios for climate adaptation: Practitioners' perspectives on a popular planning method. *Environmental Science & Policy*, **104**, 13–19. https://doi.org/10.1016/j.envsci.2019.10.014

318. Buurman, J. and V. Babovic, 2016: Adaptation pathways and real options analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy and Society*, **35** (2), 137–150. https://doi.org/10.1016/j.polsoc.2016.05.002

319. de Brito, M.M. and M. Evers, 2016: Multi-criteria decision-making for flood risk management: A survey of the current state of the art. *Natural Hazards and Earth System Sciences*, **16** (4), 1019–1033. https://doi.org/10.5194/nhess-16-1019-2016

320. Fu, X., H. Goddard, X. Wang, and M.E. Hopton, 2019: Development of a scenario-based stormwater management planning support system for reducing combined sewer overflows (CSOs). *Journal of Environmental Management*, **236**, 571–580. https://doi.org/10.1016/j.jenvman.2018.12.089

321. Gray, S., C. O'Mahony, J. Hills, B. O'Dwyer, R. Devoy, and J. Gault, 2020: Strengthening coastal adaptation planning through scenario analysis: A beneficial but incomplete solution. *Marine Policy*, **111**, 102391. https://doi.org/10.1016/j.marpol.2016.04.031

322. Guthrie, G., 2019: Real options analysis of climate-change adaptation: Investment flexibility and extreme weather events. *Climatic Change*, **156** (1), 231–253. https://doi.org/10.1007/s10584-019-02529-z

323. Hallegatte, S., 2009: Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19** (2), 240–247. https://doi.org/10.1016/j.gloenvcha.2008.12.003

324. Hobbs, B., P.T. Chao, and B.N. Venkatesh, 1997: Using decision analysis to include climate change in water resources decision making. *Climatic Change*, **37**, 177–202. https://doi.org/10.1023/a:1005376622183

325. Kwakkel, J.H., 2020: Is real options analysis fit for purpose in supporting climate adaptation planning and decision-making? *WIREs Climate Change*, **11** (3), e638. https://doi.org/10.1002/wcc.638

326. Kwakkel, J.H., M. Haasnoot, and W.E. Walker, 2016: Comparing Robust Decision-Making and Dynamic Adaptive Policy Pathways for model-based decision support under deep uncertainty. *Environmental Modelling & Software*, **86**, 168–183. https://doi.org/10.1016/j.envsoft.2016.09.017

327. Lempert, R., S.W. Popper, and S.C. Bankes, 2010: Robust decision making: Coping with uncertainty. *The Futurist*, **44** (1), 47–48. https://www.proquest.com/openview/624dcdc33173abd5dff56acf88baf624/1?pq-origsite=gscholar&cbl=47758

328. Lempert, R., J. Syme, G. Mazur, D. Knopman, G. Ballard-Rosa, K. Lizon, and I. Edochie, 2020: Meeting climate, mobility, and equity goals in transportation planning under wide-ranging scenarios. *Journal of the American Planning Association*, **86** (3), 311–323. https://doi.org/10.1080/01944363.2020.1727766

329. Li, J. and C.E. Landry, 2018: Flood risk, local hazard mitigation, and the community rating system of the National Flood Insurance Program. *Land Economics*, **94** (2), 175–198. https://doi.org/10.3368/le.94.2.175

330. Maanan, M., M. Maanan, H. Rueff, N. Adouk, B. Zourarah, and H. Rhinane, 2018: Assess the human and environmental vulnerability for coastal hazard by using a multi-criteria decision analysis. *Human and Ecological Risk Assessment: An International Journal*, **24** (6), 1642–1658. https://doi.org/10.1080/10807039.2017.1421452

331. Moallemi, E.A., S. Elsawah, and M.J. Ryan, 2020: Robust decision making and Epoch–Era Analysis: A comparison of two robustness frameworks for decision-making under uncertainty. *Technological Forecasting and Social Change*, **151**, 119797. https://doi.org/10.1016/j.techfore.2019.119797

332. Norton, R.K., S. Buckman, G.A. Meadows, and Z. Rable, 2019: Using simple, decision-centered, scenario-based planning to improve local coastal management. *Journal of the American Planning Association*, **85** (4), 405–423. https://doi.org/10.1080/01944363.2019.1627237

333. Shepherd, T.G., E. Boyd, R.A. Calel, S.C. Chapman, S. Dessai, I.M. Dima-West, H.J. Fowler, R. James, D. Maraun, O. Martius, C.A. Senior, A.H. Sobel, D.A. Stainforth, S.F.B. Tett, K.E. Trenberth, B.J.J.M. van den Hurk, N.W. Watkins, R.L. Wilby, and D.A. Zenghelis, 2018: Storylines: An alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change*, **151** (3), 555–571. https://doi.org/10.1007/s10584-018-2317-9

334. Suarez, P., J. Mendler de Suarez, B. Koelle, and M. Boykoff, 2014: Ch. 9. Serious fun: Scaling up community-based adaptation through experiential learning. In: *Community-Based Adaptation to Climate Change: Scaling it up*. Schipper, E.L., J. Ayers, H. Reid, S. Huq, and A. Rahman, Eds. Routledge, London, UK, 136–151. https://doi.org/10.4324/9780203105061

335. Totin, E., J.R. Butler, A. Sidibé, S. Partey, P.K. Thornton, and R. Tabo, 2018: Can scenario planning catalyse transformational change? Evaluating a climate change policy case study in Mali. *Futures*, **96**, 44–56. https://doi.org/10.1016/j.futures.2017.11.005

336. Moser, S.C., 2013: PIRCA Evaluation: Development, Delivery, and Traceable Impacts—With Particular Emphasis on the Contributions of the Pacific RISA. Contribution to the Ongoing Pacific RISA, Phase II, Evaluation. Susanne Moser Research & Consulting, Santa Cruz, CA, 60 pp. https://www.pacificrisa.org/wp-content/uploads/2012/01/PIRCA-Evaluation_PRISA_Yr3_final.pdf

337. Lemos, M.C., H. Eakin, L. Dilling, and J. Worl, 2019: Social sciences, weather, and climate change. *Meteorological Monographs*, **59**, 26.1–26.25. https://doi.org/10.1175/amsmonographs-d-18-0011.1

338. Gerst, M.D., M.A. Kenney, A.E. Baer, A. Speciale, J.F. Wolfinger, J. Gottschalck, S. Handel, M. Rosencrans, and D. Dewitt, 2020: Using visualization science to improve expert and public understanding of probabilistic temperature and precipitation outlooks. *Weather, Climate, and Society*, **12** (1), 117–133. https://doi.org/10.1175/wcas-d-18-0094.1

339. Gerst, M.D., M.A. Kenney, and I. Feygina, 2021: Improving the usability of climate indicator visualizations through diagnostic design principles. *Climatic Change*, **166** (3-4), 33. https://doi.org/10.1007/s10584-021-03109-w

340. Wyborn, C., L. van Kerkhoff, M. Dunlop, N. Dudley, and O. Guevara, 2016: Future oriented conservation: Knowledge governance, uncertainty and learning. *Biodiversity and Conservation*, **25** (7), 1401–1408. https://doi.org/10.1007/s10531-016-1130-x

341. Adger, W.N., K. Brown, J. Fairbrass, A. Jordan, J. Paavola, S. Rosendo, and G. Seyfang, 2003: Governance for sustainability: Towards a 'thick' analysis of environmental decisionmaking. *Environment and Planning A: Economy and Space*, **35** (6), 1095–1110. https://doi.org/10.1068/a35289

342. Biesbroek, R., J. Dupuis, A. Jordan, A. Wellstead, M. Howlett, P. Cairney, J. Rayner, and D. Davidson, 2015: Opening up the black box of adaptation. *Nature Climate Change*, **5**, 493–494. https://doi.org/10.1038/nclimate2615

343. de Bremond, A., B.L. Preston, and J. Rice, 2014: Improving the usability of integrated assessment for adaptation practice: Insights from the U.S. Southeast energy sector. *Environmental Science & Policy*, **42**, 45–55. https://doi.org/10.1016/j.envsci.2014.05.004

344. Dewulf, A., N. Klenk, C. Wyborn, and M.C. Lemos, 2020: Usable environmental knowledge from the perspective of decision-making: The logics of consequentiality, appropriateness, and meaningfulness. *Current Opinion in Environmental Sustainability*, **42**, 1–6. https://doi.org/10.1016/j.cosust.2019.10.003

345. Dilling, L., M.C. Lemos, and N. Singh, 2021: Commentary: First, do no harm: Scaling usable knowledge for just and equitable outcomes. *Global Environmental Change*, **71**, 102404. https://doi.org/10.1016/j.gloenvcha.2021.102404

346. Levine, J., K.M.A. Chan, and T. Satterfield, 2015: From rational actor to efficient complexity manager: Exorcising the ghost of *Homo economicus* with a unified synthesis of cognition research. *Ecological Economics*, **114**, 22–32. https://doi.org/10.1016/j.ecolecon.2015.03.010

347. Luan, S., J. Reb, and G. Gigerenzer, 2019: Ecological rationality: Fast-and-frugal heuristics for managerial decision making under uncertainty. *Academy of Management Journal*, **62** (6), 1735–1759. https://doi.org/10.5465/amj.2018.0172

348. LeRoy, S., R. Wiles, P. Chinowsky, J. Helman, 2019: High Tide Tax: The Price to Protect Coastal Communities from Rising Seas. Center for Climate Integrity. https://www.climatecosts2040.org/files/ClimateCosts2040_Report.pdf

349. Clavet, C., C. Topik, M. Harrell, P. Holmes, R. Healy, and D. Wear, 2021: Wildfire Resilience Funding: Building Blocks for a Paradigm Shift. The Nature Conservancy. https://www.nature.org/content/dam/tnc/nature/en/documents/WildfireResilienceFunding_TNC_6-30-21.pdf

Fifth National Climate Assessment: Chapter 32

# Mitigation

# Chapter 32. Mitigation

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# Introduction

Mitigation refers to efforts to reduce emissions or to remove carbon from the atmosphere with the goal of avoiding or reducing the effects of climate change, which is different from adapting systems and activities to a changed climate (Ch. 31). To meet international climate goals, global carbon dioxide ($CO_2$) emissions would need to reach net zero by around 2050 (KM 32.1).[1]

Mitigation is the most cost-effective response to climate change, with potentially large benefits to economies (Ch. 19), social and economic equity (Ch. 12), human health (Chs. 13, 14, 15), food security (Ch. 6), and ecosystems (Chs. 7, 8). Modeling studies agree that large near-term decreases in greenhouse gases (GHGs) in the United States are feasible by improving energy efficiency, electrifying end uses of energy, and generating electricity from non-emitting energy sources such as solar and wind (KM 32.2). However, the optimal mix of technologies to reach net-zero emissions is not yet clear, and further research and development is needed to determine the best options for long-duration energy storage, non-emitting and dispatchable (sometimes called firm) sources of electricity, and net-zero options for aviation and long-distance freight transport, as well as carbon dioxide removal (KM 32.3). Actions to immediately and substantially reduce emissions are available, and can be supported by individual choices and decisions by multiple stakeholders (KM 32.5). Further, racial, economic, demographic, and geographic inequities and injustices are embedded within existing infrastructure and social systems, and mitigation will both influence and be influenced by equity, environmental, and economic factors (KM 32.4).

## Key Message 32.1

## Successful Mitigation Means Reaching Net-Zero Emissions

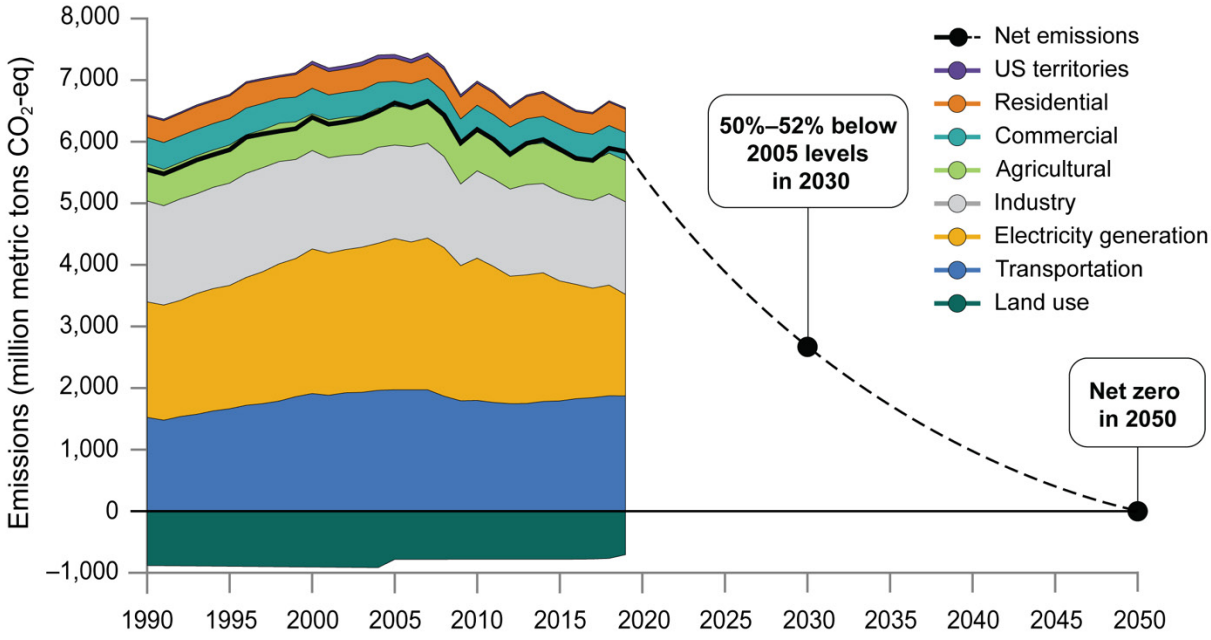
Greenhouse gas emissions in the United States decreased by 12% between 2005 and 2019, mostly due to replacing coal-fired electricity generation with natural gas–fired and renewable generation (*very high confidence*). However, US net greenhouse gas emissions remain substantial and would have to decline by more than 6% per year on average, reaching net zero around midcentury, to meet current national climate targets and international temperature goals (*very high confidence*).

### *Mitigation Goals*

To achieve the Paris Agreement (an international treaty on climate change) goal of limiting global warming to well below 2°C above preindustrial levels and pursuing efforts to limit global warming to 1.5°C above preindustrial levels, global $CO_2$ emissions need to reach net zero around 2050 and remain net zero or net negative afterward.[2] Thus, US $CO_2$ emissions reaching net zero around midcentury would be consistent with Paris goals, although a wide range of trajectories is possible based on considerations of international equity, burden-sharing, costs, and policy assumptions.[3,4,5] This chapter addresses pathways and options for mitigation of US emissions from all sectors consistent with national and international climate goals.

As part of the Paris Agreement, countries communicate nationally determined contributions (NDCs)—emissions-reduction targets that they intend to achieve. The latest NDC communicated by the United States to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat sets an economy-wide target of reducing all its net GHG emissions (not only $CO_2$) by 50%–52% below 2005 levels in 2030, or roughly –6% per year beginning in 2022, putting the country on a path to achieve the goal of reaching net-zero GHG emissions by no later than 2050 (Figure 32.1).[6] In addition, 24 states and Washington, DC, have their own reduction targets (KM 32.5).

### US Greenhouse Gas Emissions by Sector with 2030 and 2050 Goals Added




**US emissions will need to decrease rapidly to reach levels consistent with international climate targets.**

**Figure 32.1.** Figure shows US annual greenhouse gas emissions and sinks from 2005 to 2019, as well as future targets for achieving the US nationally determined contribution under the Paris Agreement. US territories—including American Sāmoa, Commonwealth of the Northern Mariana Islands, Federated States of Micronesia, Guam, Republic of the Marshall Islands, and Republic of Palau—contribute minor emissions (not visible) that are not broken down by sector. $CO_2$-eq = carbon dioxide equivalent. Adapted from DOS and EOP 2021.[6]

## *Major Trends*

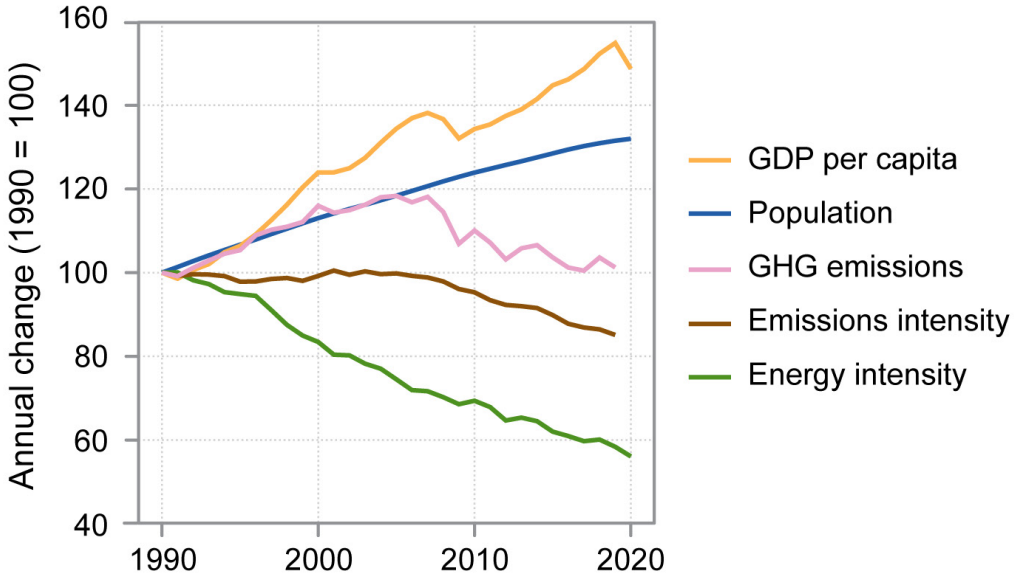
Between 1990 and 2019, US $CO_2$ and nitrous oxide ($N_2O$) emissions increased by approximately 3% in each case. Emissions of fluorinated gases increased by 86%, and methane ($CH_4$) emissions decreased by 15%.[7] Although the latest EPA inventory reports emissions through 2021,[8] this chapter focuses on trends in emissions to 2019 because the COVID-19 pandemic caused substantial but largely temporary changes in energy-related emissions worldwide (see, e.g., Davis et al. 2022;[9] Liu et al. 2020[10]). The EPA estimates that US carbon dioxide equivalent ($CO_2$-eq) GHG emissions were about 6.6 billion metric tons (or gigatons; Gt) in 2019, 2% more than in 1990.[7,11] The sources of these emissions are primarily electricity generation, transportation, and combustion of fuels in other sectors (i.e., commercial, residential, and industrial), with smaller contributions from agriculture, industrial processes, and waste (Figure 32.1). Major sinks were land-use change and especially forests, which resulted in net uptake of 0.7 Gt of $CO_2$ in 2019. Net GHG emissions from all sources and sinks were thus 5.8 Gt of $CO_2$-eq in 2019.[7,8,11]

Between 2005 and 2019, US GHG emissions decreased by 12%, mainly because of reductions in electricity generation emissions. Indeed, since 2017, the largest share of GHG emissions has come from the transportation sector (Figure 32.1). Estimates include emissions occurring within all US territories, as annually reported to the UNFCCC Secretariat by the EPA. Independent estimates by other scientific bodies and researchers are similar but not identical.[12,13,14,15]

## Sector-Specific Trends and Drivers

Between 1990 and 2019, economic and population growth have acted to increase US energy-related emissions but have been counterbalanced by reductions in both the energy used per dollar of GDP (or "energy intensity of economic activity") and the $CO_2$ emissions per unit of energy used (or "emissions intensity of energy").[16] In particular, decreases in energy emissions since 2007 were driven by a steady and substantial fall in $CO_2$ emissions per unit of energy consumed from a maximum of 59 million metric tons (megatons; Mt) of $CO_2$ per exajoule ($10^{18}$ joules) of energy consumed in 2007 to 51 Mt per exajoule in 2019 (Figure 32.2).

### Changes in Drivers for Energy-Related Greenhouse Gas (GHG) Emissions



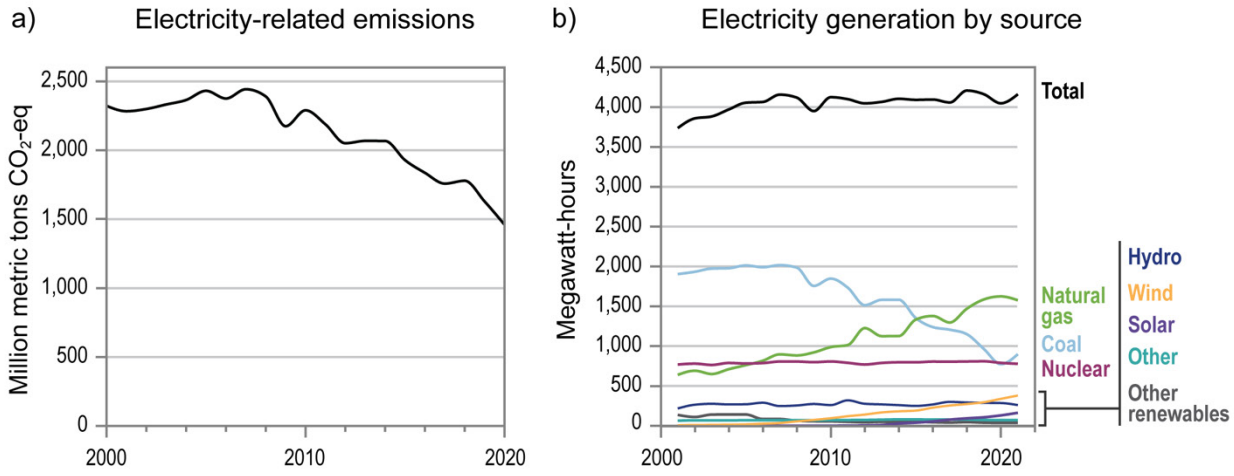

**US greenhouse gas emissions have dropped even as population and economic activity (as measured by GDP) have climbed.**

**Figure 32.2.** Energy-related greenhouse gas (GHG) emissions in the United States have declined since 2007 (pink) despite rising population (blue) and economic activity measured by the GDP (orange). Behind the decreasing trend are gradual reductions in energy use per dollar of GDP (energy intensity, green) and large decreases in GHG emissions per unit of energy produced (emissions intensity, brown). Figure credit: Stanford University.

## Electricity Sector Emissions

GHG emissions from the electricity sector in 2019 were 1,629 Mt of $CO_2$-eq, or 30% of energy-related emissions.[7] Decreases in US energy-related emissions since 2007 mostly reflect changes in the electricity sector, especially the retirement and reduced use of coal-fired power plants and corresponding increases in lower-cost electricity from natural gas–fired power plants (and to a lesser extent renewable technologies; Figure 32.3b). US emissions from electricity generation in 2019 were roughly 40% below 2005 levels (Figure 32.3a).

### Trends in Electricity Generation by Source and Related $CO_2$ Emissions



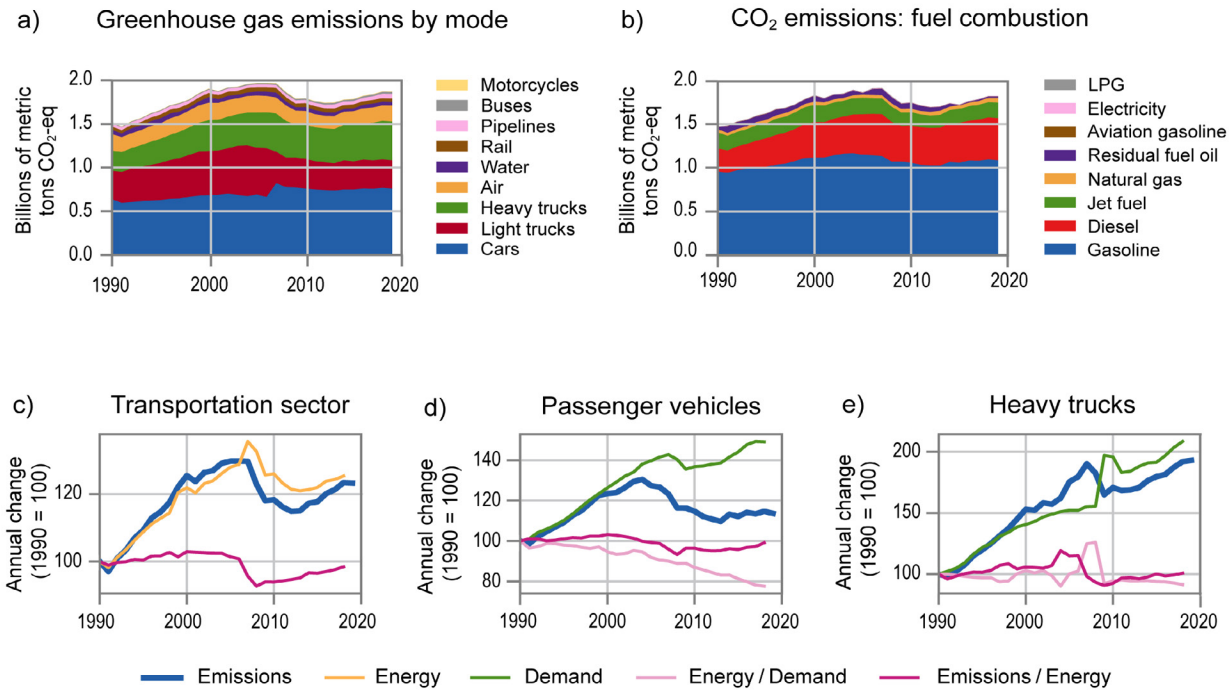

**Carbon dioxide ($CO_2$) emissions from electricity generation decreased by almost 40% between 2005 and 2020.**

**Figure 32.3.** The decrease in electricity-related emissions between 2000 and 2020 (**a**) can be explained by the decline in high-emitting coal generation and the growth in generation from lower-emitting (natural gas) and non-emitting (wind and solar) sources (**b**). $CO_2$-eq = carbon dioxide equivalent. Adapted from Scott Institute for Energy Innovation 2017[17] [CC BY-SA 4.0].

## *Transportation Sector Emissions*

GHG emissions from the transportation sector in 2019 were 1,874 Mt of $CO_2$-eq.[7] Most transportation emissions are $CO_2$ emissions from combustion of gasoline (59.6%, mostly for light trucks and cars), diesel (26.4%, mostly for heavy trucks, buses, and trains), and jet fuel (9.8%; Figure 32.4). In contrast to electricity sector emissions, transportation emissions increased by 23% between 1990 and 2018, largely reflecting 49% growth in demand for passenger vehicle transport over the period (measured in passenger-kilometers, or the distance traveled in km multiplied by the number of passengers), which was partially offset by a 22% decrease in energy required per passenger-kilometer. Over the same 1990–2018 time period, demand for heavy trucks (measured in vehicle-kilometer, or the total distance traveled by the truck fleet) more than doubled, and improvements in energy per vehicle-kilometer were more modest (an 8.6% decrease in energy required per vehicle-kilometer).

## Trends in Transportation Emissions and Underlying Drivers



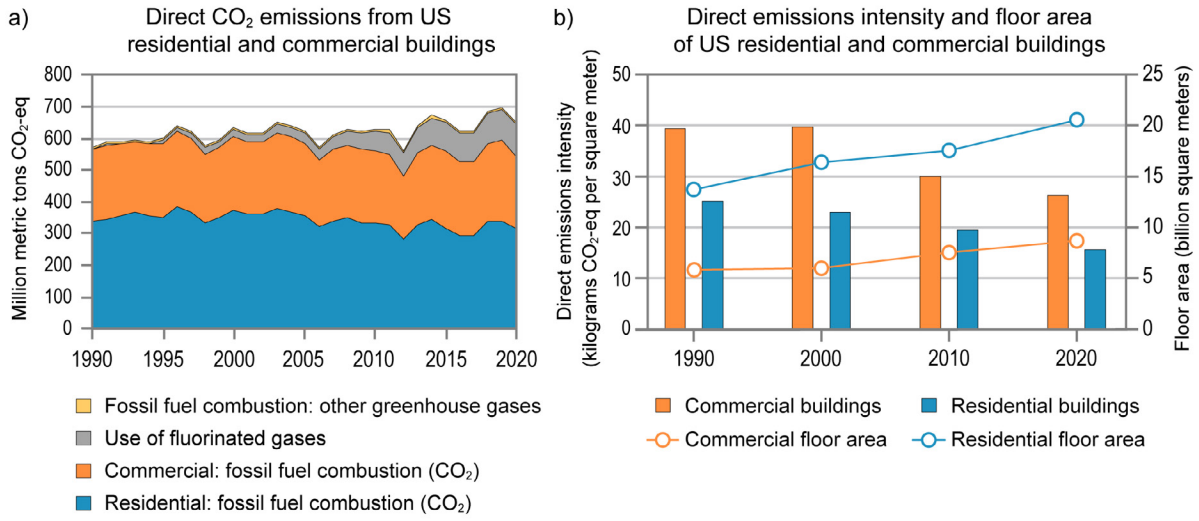

**Transportations emissions fell from 2007–2012 but have climbed since then.**

**Figure 32.4.** The figure shows US greenhouse gas emissions by transportation mode. Emissions from transportation decreased starting in 2007 (**a**), reflecting decreases in carbon dioxide ($CO_2$) emissions from fuel combustion (**b**), but both have increased again since 2012. The trend was consistent across different types of vehicles, driven by a drop in demand during a period of recession and high fuel prices (**c**, **d**, **e**). Passenger vehicles include cars, light trucks, and buses. LPG refers to liquified petroleum gas or propane; $CO_2$-eq = carbon dioxide equivalent. Figure credit: Stanford University.

## *Residential- and Commercial-Building Sector Emissions*

Direct GHG emissions from residential and commercial buildings were 699 Mt $CO_2$-eq in 2019. Since 1990, direct emissions from US residential and commercial buildings (i.e., excluding electricity) have risen by roughly 14% (Figure 32.5a). The increase is primarily related to steady growth of fugitive emissions of fluorinated gases from building cooling systems.[8] Over the same period, energy efficiency improvements and increasing electrification have kept flat direct $CO_2$ emissions from onsite fuel combustion despite 50% increases in both residential and commercial building floor area (Figure 32.5b).[18,19]

## Trends in Residential- and Commercial-Building Emissions and Intensities




**Overall greenhouse gas emissions from buildings have climbed despite small declines in $CO_2$ emissions from onsite combustion of fossil fuels.**

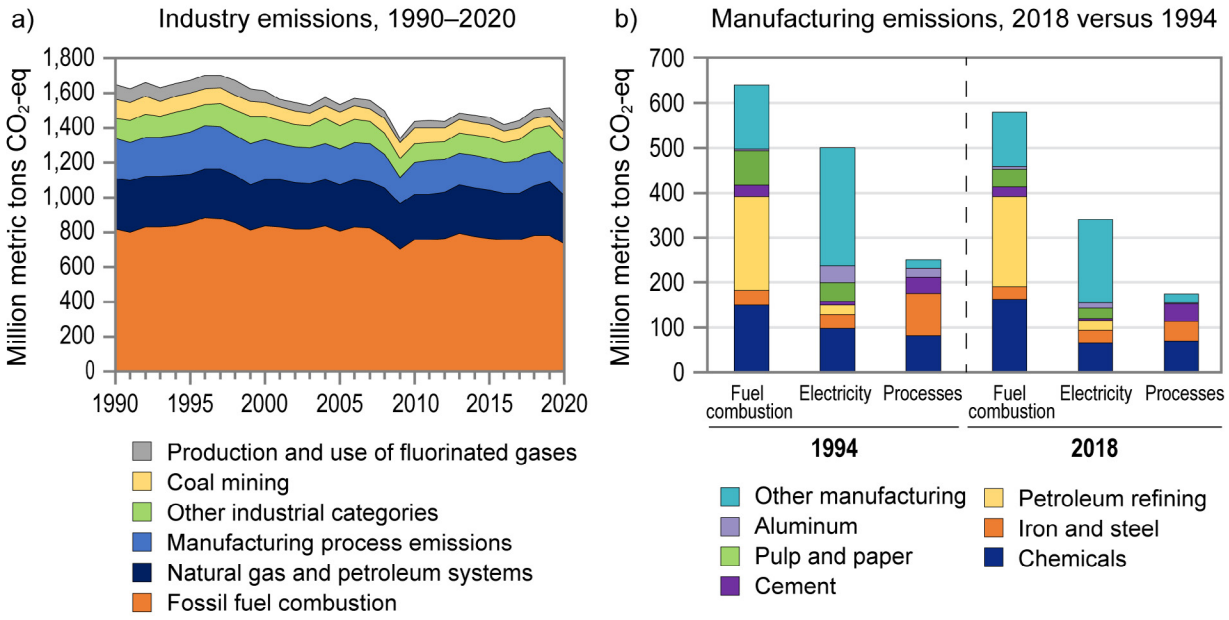
**Figure 32.5.** Carbon dioxide ($CO_2$) emissions from onsite fuel combustion in US buildings have decreased modestly since 2005 (**a**), driven by decreasing fuel-related emissions per building floor area (**b**), but overall related greenhouse gas emissions from buildings have increased over the same period due to both growth in the size of floor area (lines in panel b) and increasing levels of fluorinated gases escaping from building cooling systems (gray area in panel a). $CO_2$-eq = carbon dioxide equivalent. Figure credit: University of California, Santa Barbara.

## *Industrial Sector Emissions*

GHG emissions from the industrial sector were 1,568 Mt of $CO_2$-eq in 2019.[8] Direct emissions from the industrial sector, including onsite fuel combustion as well as all process and fugitive GHG emissions (e.g., emissions from calcination of limestone in cement production and methane leakage from oil and gas infrastructure), decreased by 14% between 1990 and 2020, primarily due to decreases in total fossil fuel combustion, fluorinated gas production and use, and metals-related process emissions (Figure 32.6). The manufacturing sector (i.e., production of goods and materials) is the largest source of direct emissions within the overall industrial sector and accounts for substantial electricity sector emissions related to purchases of power and heat (Figure 32.6b). Six key manufacturing subsectors (petroleum refining, chemicals, cement, iron and steel, aluminum, and forest products) account for around 70% of all emissions attributable to the manufacturing sector (Figure 32.6b).

Between 1994 and 2018, electricity-related emissions from US manufacturing have decreased by about 32% due to improved process efficiencies, deployment of combined heat and power systems, and decarbonization of purchased electricity. However, direct emissions from onsite fossil fuel combustion have decreased by only 10% over the same period and now account for about three-quarters of direct manufacturing emissions (Figure 32.6b).

## Trends in Industry Emissions



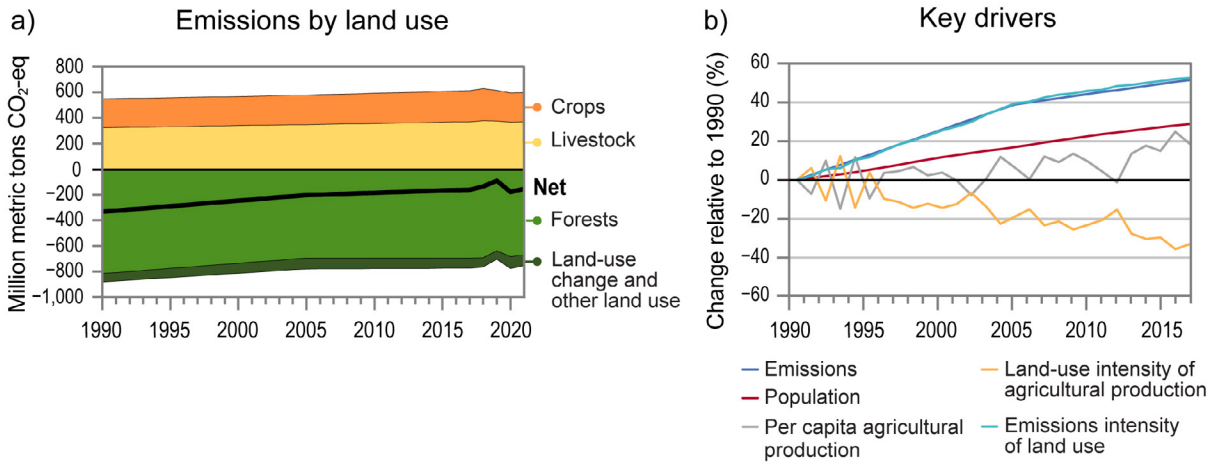

**Greenhouse gas emissions from US industry, including manufacturing, have declined in recent decades.**

**Figure 32.6.** Greenhouse gas emissions from US industry have declined modestly since 2005 across all sources (**a**). Panel **b** shows the breakdown of industry emissions in 1994 and 2018 by key manufacturing subsectors such as chemicals, iron and steel, pulp and paper, and aluminum. Data on intensity of industry emissions over time are not available. $CO_2$-eq = carbon dioxide equivalent. Figure credit: University of California, Santa Barbara.

## *Land-Related Emissions*

Annual US GHG emissions related to land use in 2019 can be split into emissions of 615 Mt of $CO_2$-eq from agriculture and uptake of 704 Mt of $CO_2$-eq by other land use and land-use change (including forests; Figure 32.7). Thus in 2019, there was a net land-related uptake (i.e., negative emissions) of 90 Mt $CO_2$-eq. Forests take up carbon, but the amount of carbon sequestered by US forest land has decreased from 816 Mt $CO_2$ in 1990 to 638 Mt $CO_2$ in 2019[8] due to a combination of drought, wildfire, and disturbances by insects and disease (Box 7.2; KM 6.1).[20,21,22] Agricultural emissions (excluding fuel combustion) increased slightly from 548 Mt $CO_2$-eq in 1990 to 615 Mt $CO_2$-eq in 2019. The net uptake of 90 Mt $CO_2$-eq from US lands in 2019 represents a 73% decrease from the uptake of 333 Mt $CO_2$-eq in 1990.[8]

### Trends in Land-Use Greenhouse Gas Emissions and Underlying Drivers




**US forests sequester more carbon than is emitted by agriculture, but the forest sink has weakened in recent decades.**

**Figure 32.7.** Net greenhouse gas emissions from US land use are negative, meaning the carbon taken up by forests is greater than agricultural emissions (**a**). However, this net sink has weakened since 2005, driven by increases in the emissions intensity of land use (light blue curve in panel **b**) and despite decreases in the land-use intensity of agricultural production (yellow curve in panel b). $CO_2$-eq = carbon dioxide equivalent. Figure credit: University of California, Irvine.

## Key Message 32.2

## We Know How to Drastically Reduce Emissions

A US energy system with net-zero emissions would rely on widespread improvements in energy efficiency, substantial electricity generation from solar and wind energy, and widespread electrification of transportation and heating (*high confidence*). Low-carbon fuels would still be needed for some transport and industry applications that are difficult to electrify (*high confidence*). Land-related emissions in the US could be reduced by increasing the efficiency of food systems and improving agricultural practices and by protecting and restoring natural lands (*high confidence*). Across all sectors, many of these options are economically feasible now (*high confidence*).

### *Established Opportunities to Reduce Energy-Related Emissions*

In modeling studies, deeply decarbonized and net-zero-emissions energy systems share several common characteristics, but regional approaches may depend on differences in resources,[23,24] industrial bases,[25] existing infrastructure,[26,27] geography,[28] governance and politics,[29] public acceptance,[30] and broader policy priorities.[31]

#### Improve Energy Efficiency

Improving energy efficiency means supplying the same level of end-use services or output while using less energy. Efficiency of buildings and appliances can be improved by design or retrofits (e.g., better insulation),[32] as well as by optimizing control and management of devices (e.g., HVAC and lighting; KM 12.3;

Figure 5.5).[33] Further efficiency gains are available in the transportation sector: urban design can reduce travel demands;[34,35] public and active transportation modes can greatly reduce energy use per passenger-mile;[36,37] and advanced engines, electrification, reducing the weight of vehicles, and aerodynamic improvements can reduce energy use per passenger-mile (KM 13.3).[38,39,40] In model scenarios of energy systems that successfully reach net-zero $CO_2$ emissions, total US energy use often decreases relative to current levels, despite economic and population growth.[41,42]

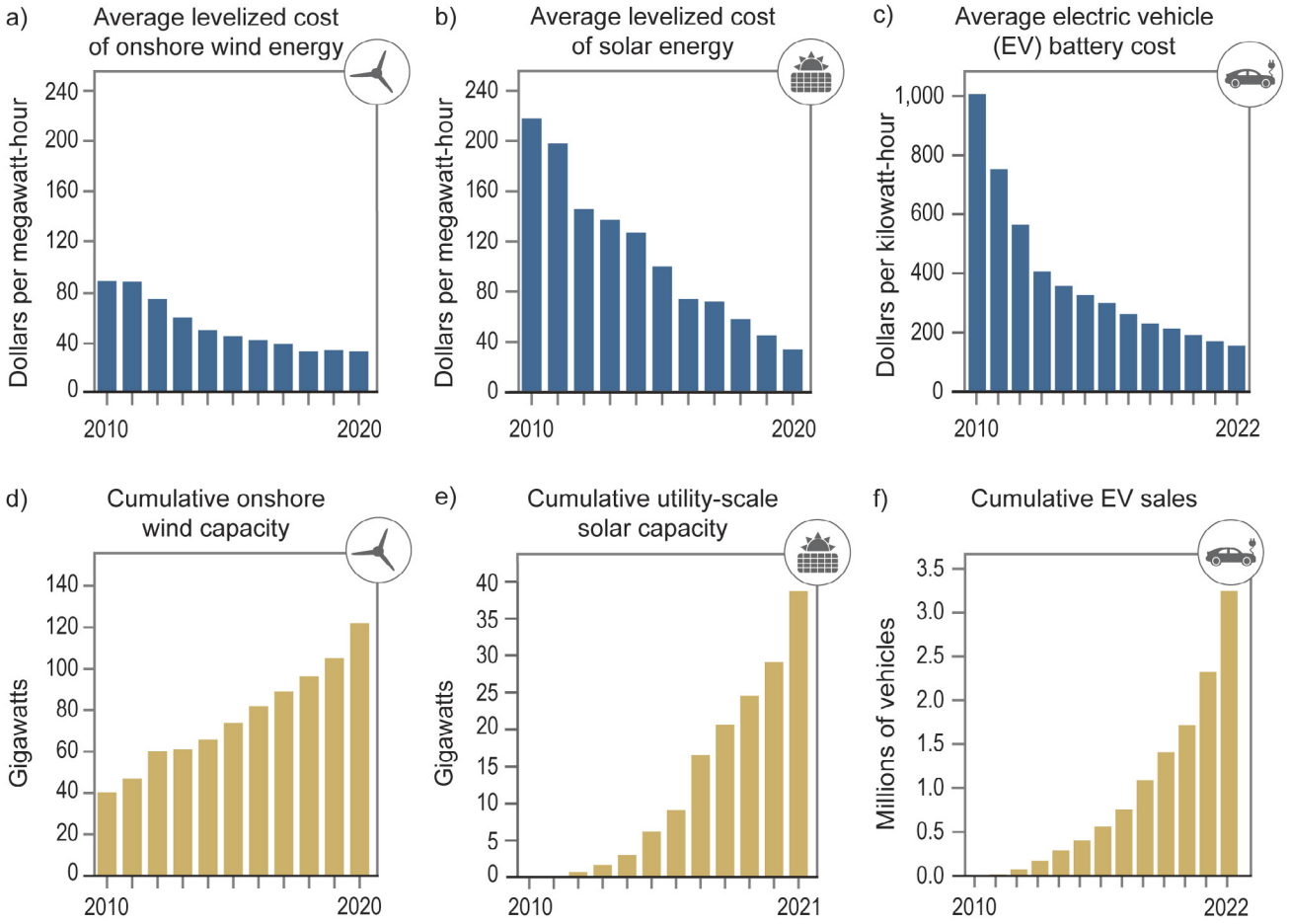
One of the concerns with energy efficiency is whether it can induce rebound effects of different types. Studies have shown that the direct rebound effect (i.e., use of more of a good or service as it becomes more affordable) is low in the context of energy goods and services, but there is more uncertainty regarding indirect rebound effects (i.e., how an increase in energy efficiency of a good or service may lead to a change in the use of other goods and services or changes in the overall economy).[43,44]

## Decarbonize the Electricity Sector

Options for reducing electricity system emissions include variable renewables (e.g., solar and wind resources, which are not available on demand; KM 5.3), dispatchable or "firm" renewables (e.g., biomass, hydropower, and geothermal, which can be available on demand), and other low-emitting dispatchable resources (e.g., nuclear and carbon capture and storage [CCS]–equipped fossil-fired generators); energy storage technologies; improved transmission (both upgrading conductors and new rights-of-way); and demand management. The rate and scale at which these technologies may be deployed in the future depend on the uncertain trajectories of their costs and energy markets, as well as a host of non-economic factors (KM 32.4).[45,46,47,48,49,50,51,52,53]

However, given their plummeting costs (Figure 32.8a, b) and growing policy support (e.g., the Inflation Reduction Act of 2022[54]), variable renewable-energy resources—especially wind and photovoltaic solar generation—are expected to play central roles in decarbonizing electricity systems across the United States. Energy system models project that the capacity of wind and solar would need to increase 2 to 10 times faster each year than maximum historical rates (Figure 32.9b) to reach the 2030 target of halving economy-wide GHG emissions and midcentury net-zero targets (Figure 32.1).[41,42] In such scenarios, expansion of energy storage generally supports greater reliance on wind and solar (Figure 32.1).[41,42]

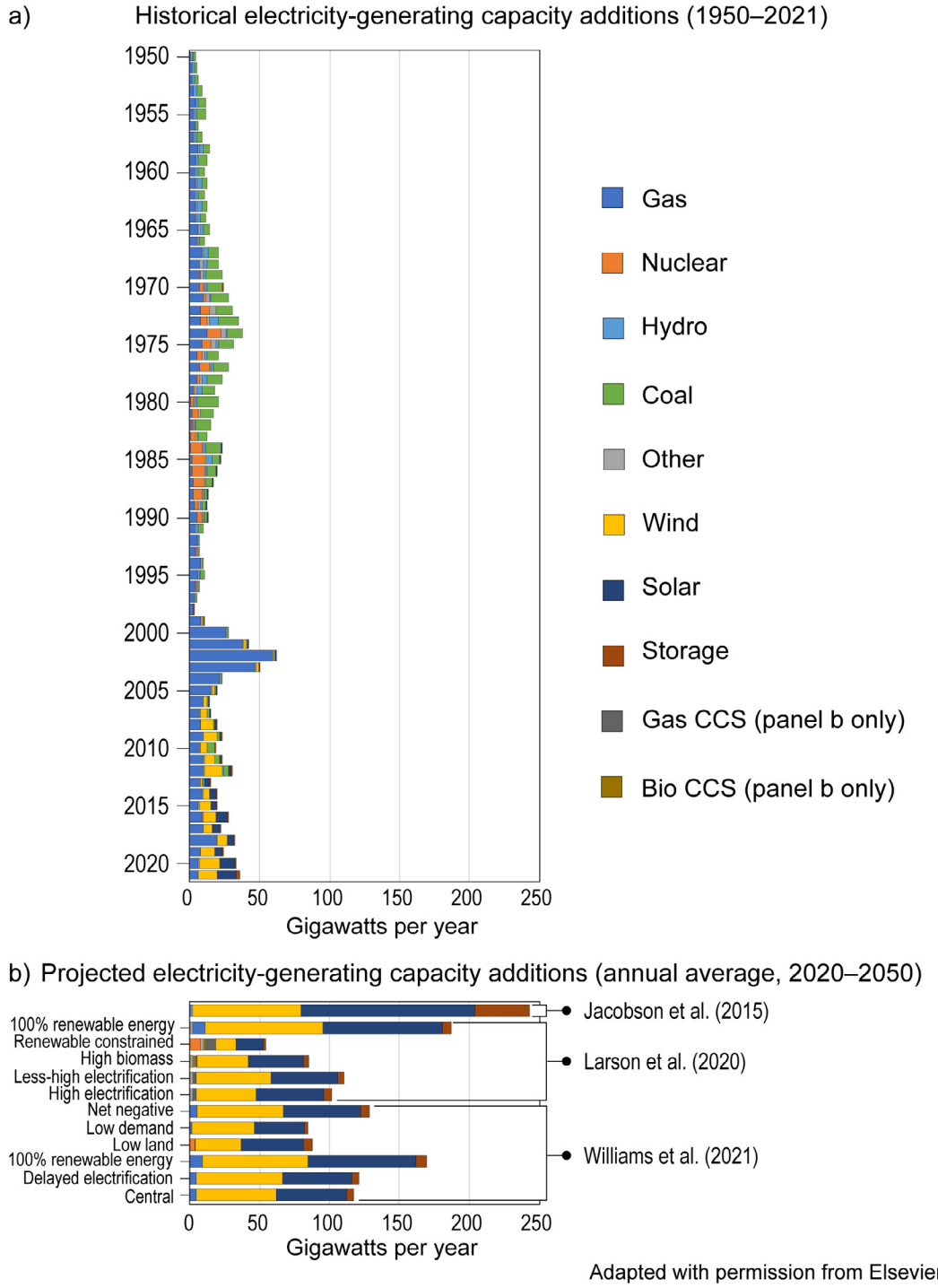
## Historical Trends in Costs and Capacity of Low-Carbon Energy Technologies in the United States




**Costs of renewable energy sources and electric vehicle batteries have declined as their cumulative deployment has increased.**

**Figure 32.8.** Costs of onshore wind (**a**), solar photovoltaics (**b**), and electric vehicle (EV) batteries (**c**) have decreased sharply since 2000 (data shown here start in 2010), as the cumulative capacities of wind and solar generation (**d**, **e**) and the cumulative number of EVs sold (**f**) have increased. Figure credit: Electric Power Research Institute, National Renewable Energy Laboratory, NOAA NCEI, and CISESS NC.

## Historical and Projected Net-Zero Annual Capacity Additions by Technology for the US Under Net-Zero Scenarios

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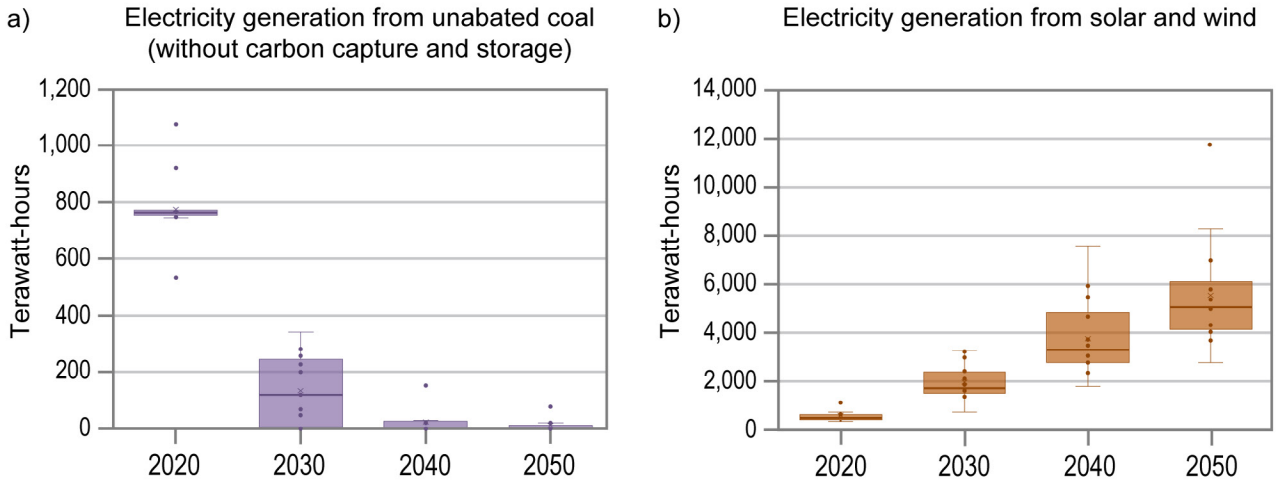
**To reach net zero, the US will need to add more electricity-generating capacity in each of the next 30 years than we have added historically.**

**Figure 32.9.** Since 1950, increases in US electricity-generating capacity have exceeded 50 gigawatts (GW) in only one year, 2002 (**a**). In comparison, scenarios of net-zero-emissions energy systems produced by models project average increases in electricity-generating capacity of more than 50 GW per year every year between 2020 and 2050 (**b**). CCS refers to carbon capture and storage. See Jacobson et al. 2015; Larson et al. 2020; and Williams et al. 2021.[49,52,59] Adapted from Bistline 2021[60] with permission from Elsevier (https://www.sciencedirect.com/journal/joule).

The same model scenarios consistently project the rapid decline of coal-fired electricity generation in decarbonized systems to near zero by 2030 (Figure 32.10).[41,42] In contrast, natural gas–fired electricity generation declines more slowly in most of these net-zero emissions scenarios, facilitating penetration of variable renewables but operating less frequently over time unless equipped with CCS.[52,55,56]

## Projected Coal and Solar/Wind Electricity Generation




**Models project a steep decline in coal-generated electricity and increases in renewables.**

**Figure 32.10.** Across net-zero scenarios produced by models, median US coal electricity generation (thick horizontal lines) is expected to decrease sharply between 2020 and 2030 (**a**). Meanwhile, in the same scenarios, median solar and wind generation would increase steadily between 2020 and 2050 (**b**). Plots show individual scenarios as points, the 25th–75th percentile ranges as rectangles, and the 10th–90th percentile ranges as thin vertical lines. The mean of each set of scenarios is represented by an X. Figure credit: University of California, Irvine, and Electric Power Research Institute.

Finally, net-zero $CO_2$ emissions scenarios often maintain—but do not greatly expand—existing nuclear and hydropower capacity in the absence of significant cost declines (such as improved economics from small modular designs; KM 5.3) and/or constraints on the deployment of other technologies.[41,42,57] In contrast, both transmission infrastructure (i.e., power lines) and international and interregional transfers of electricity often increase in decarbonization scenarios, although the scale of such increases varies.[41,42,58]

## Electrify Energy End Uses

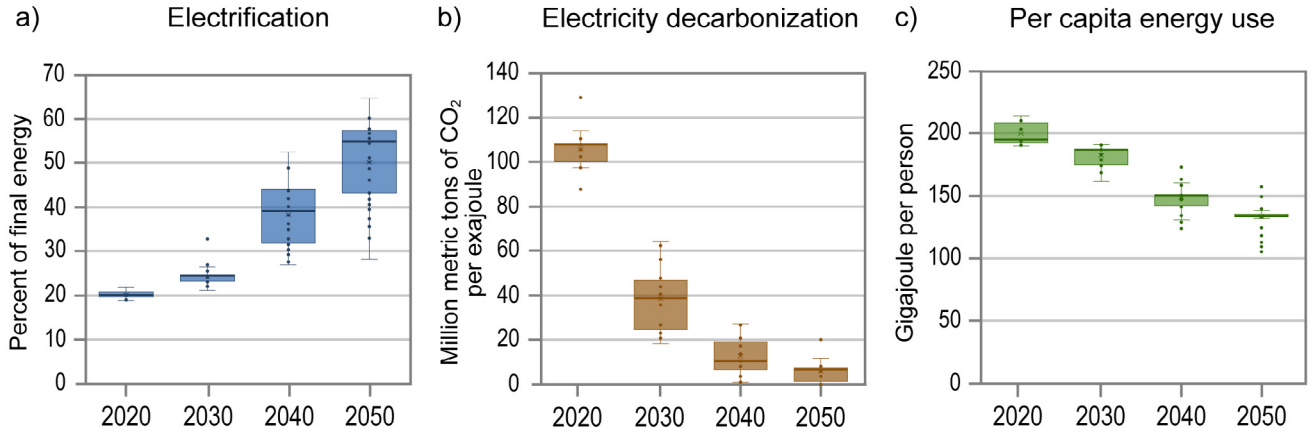
As electricity systems are decarbonized, energy model scenarios consistently project widespread electrification of energy end uses such as on-road transportation and heat for buildings and industry (KM 5.1).[41,42,49,51,52,53,61] Electricity may also be used to produce low-carbon fuels, such as hydrogen and e-fuels (liquid fuels produced by combining carbon captured from the atmosphere with hydrogen produced by electrolysis), for difficult-to-electrify applications (Box 32.1).[62] The share of US final energy demands (i.e., energy used) met by electricity in net-zero-emissions energy systems will depend on the costs of low-carbon alternatives such as biofuels and hydrogen, but estimates range from 30%–60% in 2050, up from about 20% today (Figure 32.11).[41,42]

In transportation, light-duty electric vehicles (EVs) have had policy support (e.g., tax refunds) at both the state and federal level for a long time, and new EV sales have increased in recent years (Figure 32.8).[63,64,65,66] The EV share of new light-duty vehicle sales in the US is expected to grow quickly,[66,67] which is the case in model scenarios that reach net-zero emissions by midcentury.[41,42] Many medium- and heavy-duty

vehicles can also be electrified,[68] although some applications (e.g., long-distance trips) may present special challenges.[69,70,71,72,73] Decarbonization of the most difficult-to-electrify transportation sectors (e.g., aviation, international shipping) may require liquid biofuels or fuels synthesized using electrolytic hydrogen and carbon captured from the atmosphere.[74,75]

Insofar as electricity is generated from non-emitting sources, electrification of space and water heating would drastically reduce direct emissions from residential and commercial buildings in the United States (where these end uses account for the bulk of natural gas and oil consumption).[76,77,78] Similarly, most industrial energy demand could be electrified using existing technologies,[79] although achieving net-zero emissions in some industries may present special challenges[80,81,82,83]—particularly related to the costs of supplying high-temperature heat with electricity[84] and/or fundamental changes in processes such as switching to direct reduction of iron ore with electrolytic hydrogen or installing carbon capture and storage on thousands of cement kilns worldwide.[85]

### Characteristics of US Energy Systems in Climate Mitigation Scenarios




**Net-zero model scenarios show large increases in electrical energy, accompanied by decarbonization of electricity sources and modest decreases in overall energy use per person.**

**Figure 32.11.** Across net-zero model scenarios, between 2020 and 2050 the median share of all energy used (thick horizontal lines) by end consumers that is electricity increases (**a**), the median carbon intensity of electricity decreases (**b**), and the median energy per capita decreases modestly (**c**). Plots show individual scenarios as points, the 25th–75th percentile ranges as rectangles, and the 10th–90th percentile ranges as thin vertical lines. The mean of each set of scenarios is represented by an X. $CO_2$ = carbon dioxide. Figure credit: University of California, Irvine; Electric Power Research Institute; and Evolved Energy Research.

## *Established Opportunities to Reduce Land-Related Emissions*

Despite increasing demand for food and the headwinds of climate change impacts on agriculture, there are multiple options for decreasing land-use emissions and protecting and enhancing terrestrial carbon sinks (Ch. 11).

### Use Most-Productive Land for Agriculture

Agriculture requires more land, by far, than any other human activity.[86] One way to reduce the land required to grow food is to continue farming the most productive lands (those that grow more crops per land area). Removing the most productive areas from cultivation would lead to an increase in the overall land area required for agriculture.[87] Loss of productive US farmland to sprawl or even restoration could thus lead to substantial land-use change and related GHG emissions elsewhere (e.g., if demanded agricultural goods

are imported from other regions).[88,89] For these reasons, studies have suggested mitigation efforts should prioritize restoration of marginal (i.e., not the most productive) lands.[90]

### Reduce Food Waste

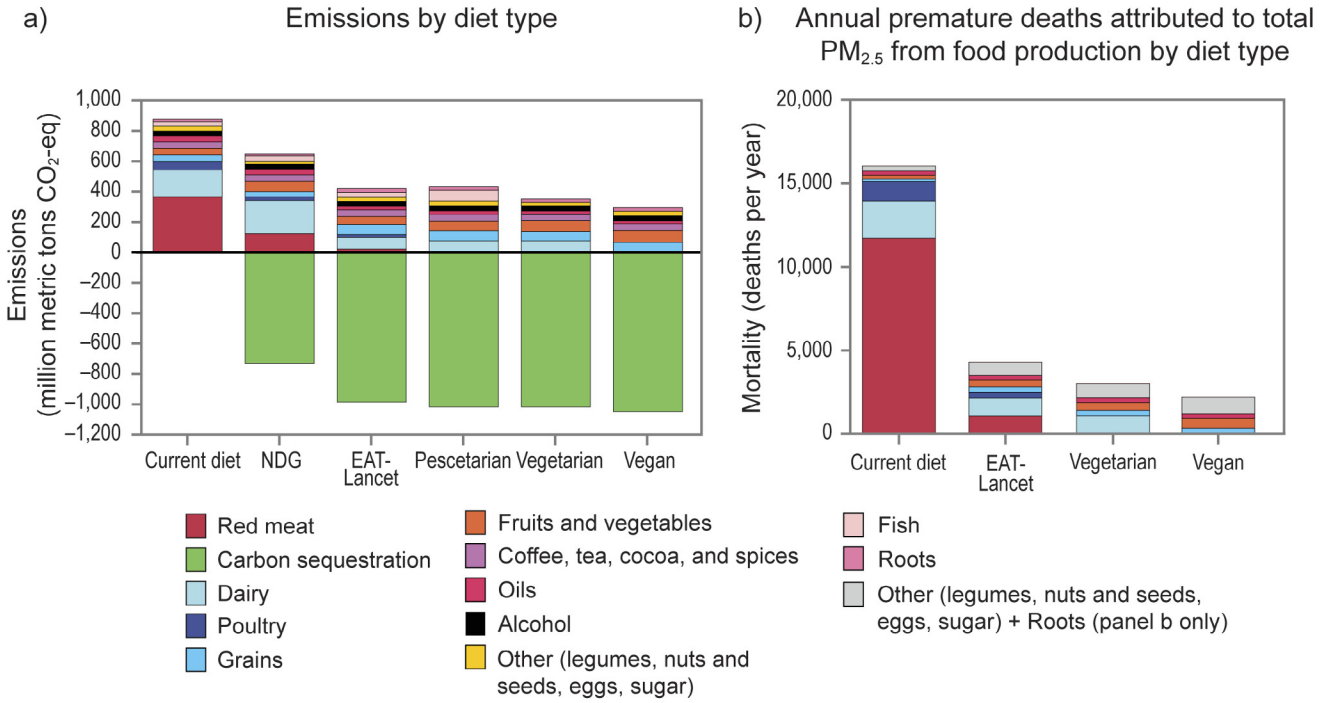
More than a third of all food in the US is currently wasted, more than 40% of which is food discarded by retailers and consumers (Box 11.2; Figure 11.12).[91,92] Multiyear campaigns (from 4 to 11 years long) in five other developed countries successfully reduced food waste per person by 8%–29% through public education and public and private initiatives.[91] Assuming similar reductions could be achieved, US agricultural land and land-related GHG emissions could be reduced by 4%–13%.

### Shift Diets

GHG emissions produced during food production, distribution, transportation, and sale at retail or restaurants vary across different foods, so that different diets will entail different levels of life-cycle GHG emissions.[93,94,95,96] In particular, although meat is a good source of protein and micronutrients, it generally produces more emissions per calorie than plant-based foods because energy is lost at each trophic level.[93] Emissions related to meat production also vary: for example, ruminant animals usually produce much more GHG emissions per calorie of meat and per gram of protein than poultry (Figure 11.8).[97] By reducing demand for emissions-intensive food, shifts to pescatarian, vegetarian, vegan, Mediterranean, or "flexitarian" (less meat consumption but not strictly vegetarian) diets can reduce land-related GHG emissions while providing direct health benefits (Figure 32.12),[94,98,99,100] although analyses and models differ as to the level of future food demand related to such diets and other socioeconomic changes.[101] Shifting diets and associated changes in agricultural practices have implications for land-use change as well as supply chains, air pollution, and human health.[102] Consideration of energy and other inputs per unit of production and the resulting impacts on net GHG emissions is important for comparison of different dietary choices.

However, 10.4% of American households are food insecure (Box 11.1),[103] so any approach to reduce the consumption of higher-emissions foods that results in higher food prices could disproportionately harm these households. Instead, policies might encourage less emissions-intensive diets while also reducing food costs and increasing consumer choice by making a diversity of plant-based and other lower-emissions, nutritious, and affordable options more widely available.

## Emissions Reductions and Related Health Benefits from Dietary Shifts




**Changes in American diets could decrease US land-use greenhouse gas emissions, increase carbon sequestration, and reduce air pollution.**

**Figure 32.12.** Studies have estimated potential reductions in greenhouse gas (GHG) emissions (**a**) and air pollution-related deaths (**b**) if the shares of foods in Americans' current (average) diet were to shift. Although the specific changes in diet vary across studies, all would reduce GHG and pollution emissions as well as enhance carbon sequestration relative to the current diet. EAT-Lancet refers to a "flexitarian" diet that is mostly plant-based but includes modest amounts of fish, meat, and dairy foods. NDG refers to government-endorsed national dietary guidelines. $PM_{2.5}$ refers to particulate matter 2.5 micrometers or smaller in diameter. $CO_2$-eq = carbon dioxide equivalent. Figure credits: (a) University of Minnesota, NOAA NCEI, and CISESS NC; (b) adapted from Domingo et al. 2021[102] [CC BY-NC-ND 4.0].

## Improve Management of Croplands and Pasture

There are numerous opportunities to decrease the intensity of emissions (and/or increase sequestration; see Box 32.2) of croplands and pasture, including 1) improving soil health, 2) improving nitrogen fertilizer management, 3) increasing the number of trees and other perennials on the landscape (e.g., by agroforestry; see Ch. 11),[104,105,106] and 4) avoiding methane emissions. Soil health and carbon sequestration can also be improved by amendments (including biochar; Figure 11.5), cover crops, reduced tillage,[107] and diversification of crop rotations.[108] Careful and sustained implementation of these practices can increase not only soil carbon but also yields, resilience, and profitability.

Better aligning the timing and amount of fertilization with plants' needs can reduce fertilizer use[109,110] and thereby also reduce both nitrous oxide ($N_2O$) emissions from the soil and fossil fuel emissions from fertilizer production. Fertilizers with synthetic nitrification inhibitors can further reduce $N_2O$ emissions.[111] Increased fertilizer efficiency and inhibition of nitrification processes in soil together can reduce $N_2O$ emissions by roughly 50%.[112,113]

There are also feasible options for reducing agricultural (livestock and rice) and waste (landfill and wastewater) sources of methane emissions.[114] Methane is a relatively short-lived GHG that has contributed

to at least 25% of climate warming to date.[115,116] Consequently, technically feasible near-term methane emissions reductions could slow global decadal warming by 30%, avoiding a quarter degree Celsius of warming by midcentury.[114] In addition to land-related sources of methane, there are large reductions possible from the oil and gas sector,[117] primarily by repairing leaks at little or no net cost[114] and ideally prioritizing disproportionately large sources (i.e., super-emitters).[118,119,120]

### Avoid Conversion and Monitor Carbon Fluxes on Unmanaged Land

Between 50 and 150 Mt of annual $CO_2$ emissions could be avoided by stopping conversions of unmanaged land in the United States (i.e., natural forests, grasslands, wetlands, or other ecosystems where there has been no substantial human influence or intervention).[121] Strategies for stopping such conversions include densification of already-developed areas, zoning, and property tax incentives, as well as land protection such as conservation easements and public parks.[122,123,124,125] Related to this opportunity, the recent decrease in carbon sequestration by US forests (KM 32.1) is a concern. Further weakening of this carbon sink would make reaching net zero proportionally that much more difficult. Improved monitoring of forest carbon fluxes and their drivers is therefore important, including those on unmanaged land and in boreal Alaska (KM 7.2).[126,127,128]

## Key Message 32.3

## To Reach Net-Zero Emissions, Additional Mitigation Options Need to Be Explored

Although many mitigation options are currently available and cost-effective, the level and types of energy technologies and carbon management in net-zero-emissions energy systems depend on still-uncertain technological progress, public acceptance, consumer choice, and future developments in institutions, markets, and policies (*high confidence*). Attractive targets for further research, development, and demonstration include carbon capture, utilization, and storage; long-duration energy storage; low-carbon fuels and feedstocks; demand management; next-generation electricity transmission; carbon dioxide removal; modern foods; and interventions to reduce industry and agricultural emissions (*medium confidence*).

## *Potential Opportunities to Reduce Energy-Related Emissions*

There are many uncertainties and outstanding questions related to mitigation of energy-related emissions. These uncertainties are reflected by the large differences in the scale and mix of energy sources and use as well as carbon management across modeled net-zero-emissions energy systems, which highlight potential mitigation opportunities.

### The Mix of Electricity Sources in Net-Zero-Emissions Energy Systems

In recently modeled net-zero-emissions US energy systems, the share of electricity demand met by variable renewables—as opposed to firm sources—varied from 45%–89% depending on the availability of energy storage, transmission, and the mix of solar and wind.[41,42] Although grid managers are gaining experience planning and operating electricity systems with large amounts of solar and wind generation, questions persist as to the maximum share of these resources that should be included in reliable and resilient decarbonized systems[129] and the best approaches for dealing with their natural variability.[130] Large shares of variable renewables can be incorporated in electricity grids through the use of 1) batteries, hydrogen, and other types of energy storage; 2) transmission and interregional transfers of electricity; 3) firm low-carbon electricity sources; and 4) greater demand-side responses. The costs and effectiveness of these approaches for managing variability differ and are related to the spatial and temporal variability of solar and wind

resources,[24,75,131,132,133,134,135,136] in addition to a host of non-cost factors (KM 32.4). Moreover, energy sources and technologies will interact in complex ways to fulfill the different functions in electricity systems (e.g., providing energy, capacity, and ancillary services over different timescales), depending on their relative costs and system benefits, policy stringency and design, geophysical resources and infrastructure, environmental co-benefits, and societal preferences.[55,56,137] Further research, development, and demonstration of technologies and approaches are needed to resolve uncertainties, identify key sensitivities, and clarify the most attractive options for providing reliable, resilient, and affordable electricity in net-zero-emissions energy systems (Figure 5.6).

### Alternative Fuels for Difficult-to-Electrify Sectors

As with electricity, there is considerable uncertainty about the scale and mix of other energy carriers (e.g., hydrogen, bioenergy, e-fuels) that may be needed by difficult-to-electrify sectors such as long-distance transportation of freight, long-haul aviation, high-temperature industrial heating, and space heating in very cold climates.[75,84,138,139,140] Hydrogen, ammonia, alcohols, and carbon-based fuels (e.g., methane, petroleum, methanol) can all be produced with low and eventually net-zero $CO_2$ emissions (Box 32.1). However, it is not clear whether producing and burning these fuels would be lower in cost and more sustainable than continuing to use fossil fuels and managing the related emissions through CCS or carbon dioxide removal (CDR; removal of $CO_2$ from the atmosphere).[62] Here again, further research, development, and demonstration of technologies will help reveal critical dependencies and trade-offs and clarify the most sustainable and cost-effective pathways to net-zero-emissions fuels.

## Box 32.1. Hydrogen

Hydrogen is an energy carrier that could link together multiple energy sectors (known as sector coupling) and facilitate high shares of variable wind and solar generation in electricity systems.[141,142] Multiple processes can produce hydrogen—including electrolysis, which uses electricity to split water into hydrogen gas ($H_2$) and oxygen gas ($O_2$). These processes represent potential links between the electricity sector, fuels for transportation and industry, and feedstock for chemical materials.

Some electrolyzers (e.g., proton exchange membrane) can also be ramped up and down in seconds[143,144] to help manage electricity demand in energy systems with variable electricity sources.[142,145] Other means of producing hydrogen with low or no $CO_2$ emissions, such as methane or biomass pyrolosis and steam methane reforming (SMR) with carbon capture, utilization, and storage (CCUS),[142,146,147] may also contribute to decarbonization if life-cycle GHG emissions can be kept low,[148,149] but these will not facilitate sector coupling or act as flexible electricity demand.

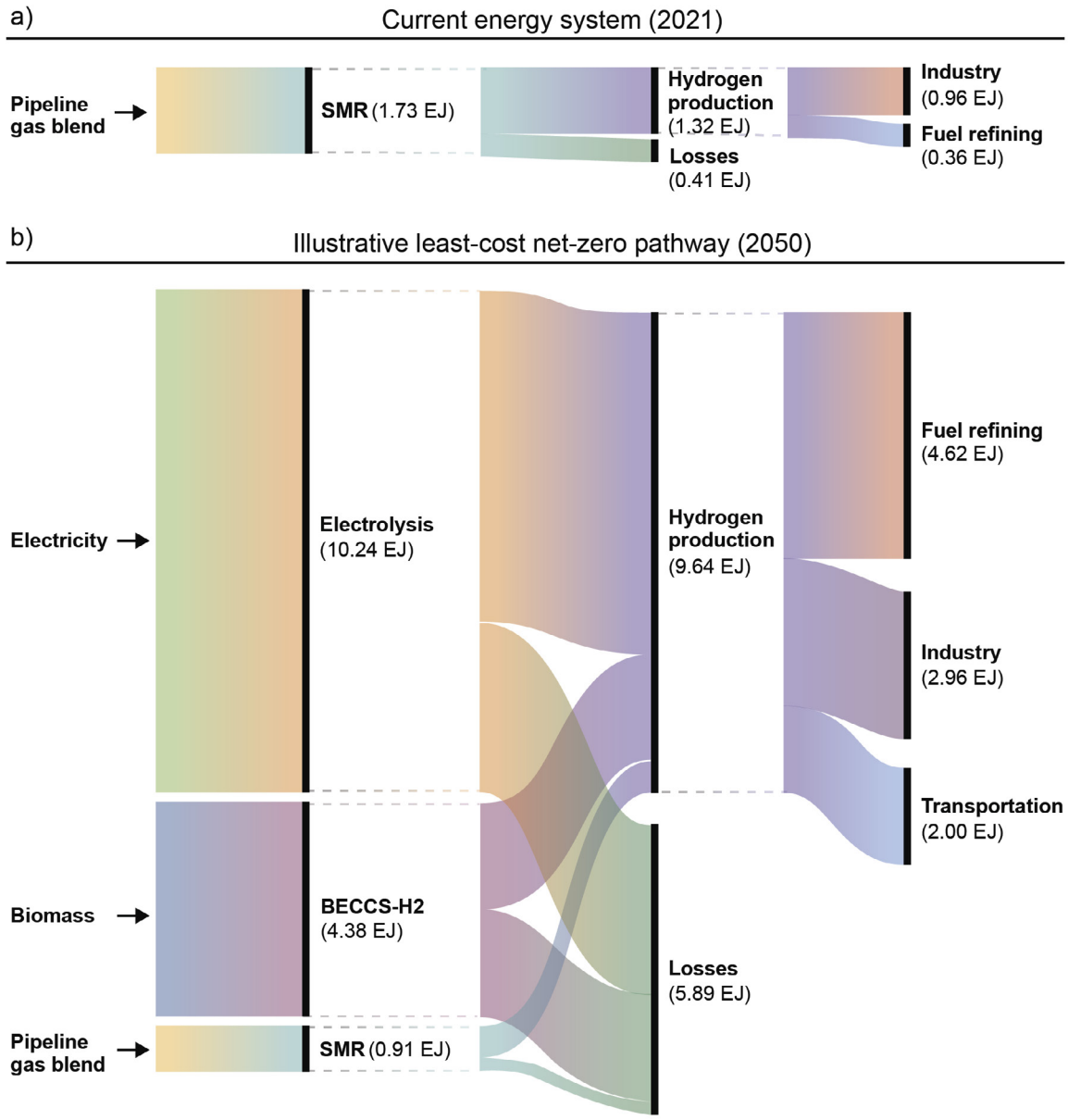
Global hydrogen demand was 90 Mt in 2020 and was supplied almost exclusively by fossil fuel feedstocks: 59% by natural gas without CCUS, 19% by coal, 21% from by-product processes that often contain a mixture of other gases, and less than 1% each of natural gas with CCUS, oil, and electricity (Figure 32.13).[150] Petrochemical processes were the largest sources of by-product hydrogen. Reflecting its fossil origin, hydrogen production in 2020 accounted for 900 Mt of $CO_2$ emissions.[150] Of all hydrogen produced in 2020, 44% was used in refineries, 37% in ammonia production, 14% in methanol production, and 6% in the direct reduction of iron, with other demands accounting for less than 1%.[150]

As noted in the discussion of alternative fuels (KM 32.3), hydrogen may help to decarbonize difficult-to-electrify end uses such as long-distance transport of freight and aviation, for which energy density is critical.[74,75] However, pressurizing or storing hydrogen in liquid phase for transport and storage adds additional costs and requires heavy storage tanks.[75,142] When used, hydrogen can either be oxidized in fuel cells or combusted in gas turbines[151,152] to produce electricity (or thrust) in a power-to-gas-to-power loop. Although substantial energy is lost in this loop, it allows shifting electricity in time from when it is readily available to when it is needed most.[131,134]

A key challenge is the current high cost of producing hydrogen from zero- or low-emitting processes. Hydrogen produced from carbon-emitting SMR can cost in the range of \$1–\$2.50/kg $H_2$, much lower than the more than \$4/kg $H_2$ achievable with current electrolysis technology and wind or solar power.[153,154] The US Department of Energy's Hydrogen Shot program has set a goal of achieving clean hydrogen production for \$1/kg $H_2$ within a decade by reducing both electrolyzer and

wind- and solar-electricity costs (KM 5.3).[153] There are also challenges of leakage from and embrittlement of infrastructure not originally designed for hydrogen, such as natural gas pipelines, which create concerns about safety,[142,155] the potential for increases in air pollutants such as nitrogen oxides if hydrogen is combusted,[156,157] and the climate-warming influence of fugitive hydrogen.[158,159] However, at low concentrations, hydrogen can be safely injected into natural gas pipelines and used in conventional home appliances.[160,161,162,163,164]

## Hydrogen Production by Source and End Uses in 2021 and 2050




**Energy model scenarios show that the magnitude, sources, and uses of hydrogen will change substantially by 2050.**

**Figure 32.13.** Curves in the figure show how hydrogen is produced (left), lost to waste (middle) and used (right) currently (**a**) and in an illustrative 2050 scenario (**b**). The thickness of the curves represents the amount of hydrogen in each category. Today, most hydrogen is produced by steam reforming of natural gas (SMR) and used by the chemical industry (especially for making fertilizer). In the depicted net-zero emissions scenario, by 2050 the largest source has become electricity, and fuel refining has become the largest use. BECCS-H2 refers to hydrogen produced from biomass feedstocks with carbon capture and storage; EJ = exajoule. Adapted with permission from Haley et al. 2022.[165]

## Carbon Management

Most model scenarios that reach net-zero emissions in the United States entail substantial use of CDR technologies, not as a replacement for emissions reductions but instead to offset continuing emissions from the most difficult-to-decarbonize sectors and processes, such as aviation and cement making (sources of emissions that may be much more expensive to eliminate), to offset non-energy GHG emissions, and to reduce GHG concentrations in the atmosphere. The degree and form of CDR deployment, including the balance between industrial carbon capture and intentional enhancement of natural carbon sinks, remain highly uncertain, however, and depend on technological readiness, economics, public acceptance, and institutional and political considerations (Box 32.2).

## Box 32.2. Carbon Dioxide Removal

The most recent modeling studies of net-zero emissions scenarios for the United States consistently project that some quantity of carbon dioxide removal (CDR) from the atmosphere will be needed to offset any residual greenhouse gas (GHG) emissions.[41,42] The scale of CDR called for in these scenarios ranges from 0.8–2.9 gigatons (Gt) of carbon dioxide ($CO_2$; median is 1.6 Gt) in scenarios that reach net-zero $CO_2$ emissions by 2050 (Figure 32.14).

CDR options fall into two categories according to whether they enhance uptake of atmospheric $CO_2$ by biological processes or by chemical processes, each of which can be further disaggregated depending on where the processes occur (e.g., on land, in the ocean, or in industrial facilities).[166,167] Different approaches have different biophysical and economic limits to scale,[168] as well as different concerns related to equity and environmental justice,[169,170] environmental impacts,[171] permanence or durability of removal (i.e., the timescale of sequestration and its reversibility),[172,173,174] and additionality (i.e., the removal would not have occurred without human intervention).[166,175]

Current energy models are relatively simplistic in their representation of CDR, typically including only 1) bioenergy with carbon capture and storage (BECCS), 2) afforestation/reforestation, and 3) industrial direct air capture (DAC). Among these methods, the on-land biological options (BECCS and afforestation/reforestation) are the most prevalent in net-zero emissions scenarios; BECCS dominates if underground carbon sequestration is allowed (Figure 32.14).

Most scenarios use DAC sparingly, owing to its cost and energy requirements (Figure 32.14), but recent studies have highlighted potential cost reductions.[176] Evaluations of natural climate solutions meanwhile suggest that reforestation represents the largest opportunity for land-based mitigation.[177] Up to 128 million acres of land in the US are reforestable and could sequester 200–500 million metric tons (Mt) of $CO_2$ per year[178,179] given substantial investments in the reforestation supply chain.[180]

However, a variety of other biological CDR options are being explored and could be cost-effective at carbon prices of \$50–\$100/Mt $CO_2$: improved management of rangeland and pasture might sequester 0.05–0.74 Mt of $CO_2$ per acre per year, or a total of 49–490 Mt of $CO_2$ per year, given the roughly 655 million acres of US grazing land.[121,181,182,183,184] Improved management of cropland soil (e.g., applying biochar, cover crops, or no-till) might sequester 150–250 Mt of $CO_2$ in the United States each year.[121,185,186,187,188] In forests, extending timber rotations, removing competing vegetation, and selective harvesting could remove 160–315 Mt $CO_2$ per year.[179,189,190,191,192,193,194,195,196] Finally, rewetting drained US wetlands[197,198] and reconnecting salt marshes to the ocean (which reduces methane emissions)[199] could remove 9 Mt of $CO_2$ per year.[121] These options are discussed further in other chapters (KMs 6.3, 9.2, 11.1; Boxes 7.2, 30.5; Focus on Blue Carbon).

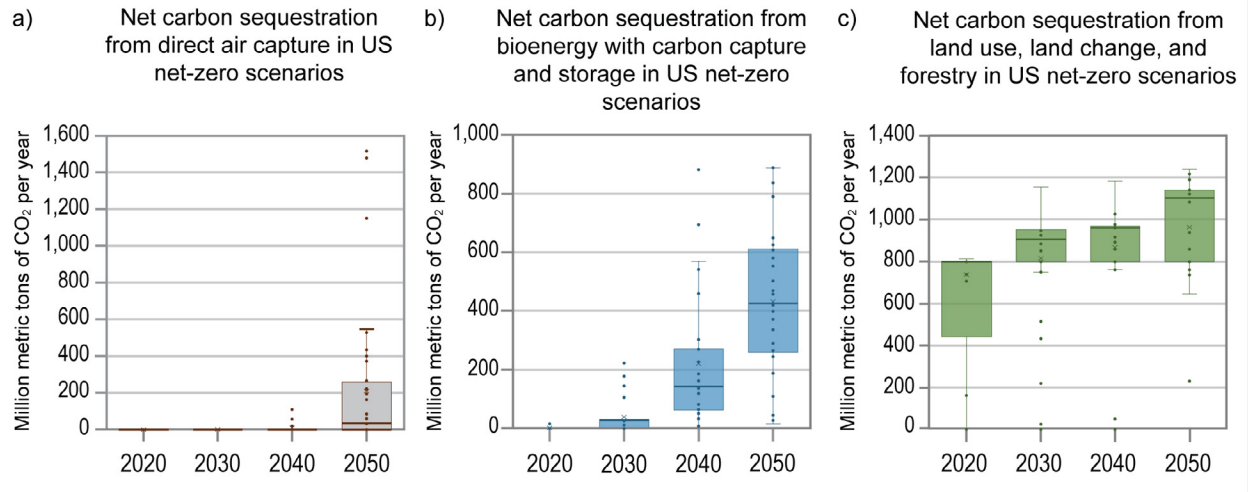
Although less mature, a growing body of research is also focusing on ocean-based CDR,[200] including ocean fertilization,[201] artificial upwelling and downwelling, seaweed farming,[202] marine restoration, ocean alkalinity enhancement,[203] and electrochemical engineering approaches (see, e.g., KM 10.3).

Additional research could reduce the uncertainty related to these estimates; establish robust monitoring, reporting, and verification protocols; and help to prioritize types and locations for CDR based on co-benefits and trade-offs. A related area of research is the Earth system response to large-scale CDR (i.e., negative emissions); a growing body of literature has shown that emitting GHGs and then removing them from the atmosphere is not the same as not emitting the GHGs at all.[204,205,206]

Reducing sunlight reaching the Earth's surface, or solar radiation modification (SRM), is sometimes discussed alongside CDR because both are intentional interventions in the climate system.[166,207] SRM is not mitigation as defined in this

chapter; the effectiveness, costs, environmental trade-offs, and geopolitical implications of SRM are uncertain, and further research on these topics is either underway or may be merited (KM 17.2). Moreover, some scientists and policymakers emphasize that the risks of SRM should be considered in the context of the many risks of continued climate change.[208]

## Scale and Type of Carbon Dioxide Removal in US Net-Zero Emissions Scenarios




**Net-zero emissions scenarios project substantial carbon dioxide removal by 2050, although the type and quantities used in the scenarios vary considerably.**

**Figure 32.14.** Annual carbon dioxide ($CO_2$) removals increase between 2020 and 2050 in scenarios that reach net zero by 2050, including nature-based sequestration on land (**c**), bioenergy with carbon capture and storage (**b**), and—after 2040—direct air capture (**a**). Median sequestration (thick horizontal lines) by land use, land-use change, and forestry increases less dramatically in scenarios. Plots show individual scenarios as points, the 25th–75th percentile ranges as rectangles, and the 10th–90th percentile ranges as thin vertical lines. The mean of each set of scenarios is represented by an X. Figure credit: University of California, Irvine.

## Changes in Transportation Modes and Behavior

Uncertain changes in mobility and travel behavior could facilitate or hinder mitigation. For example, autonomous vehicles are rapidly evolving but still need to overcome challenges of consistent safety measures, standardization of technology liability, and security and privacy concerns.[209,210] Studies have shown that autonomous vehicles could increase or decrease energy use and GHG emissions depending on the conditions of adoption and use.[211,212,213] New mobility services (e.g., ride-hailing or transit services with a monthly subscription) are becoming widespread and have the potential to transform current patterns of travel behavior, but they still face challenges of cost-competitiveness and consumer acceptance.[214,215,216] And as with automation, these mobility services may reduce emissions under a limited set of conditions (e.g., electrification and shared use cases).[213,217,218,219]

## Sector Coupling

The integration of different parts of energy systems, sometimes referred to as sector coupling, involves coordinated planning, operations, and markets for electricity, fuels, and thermal resources to meet end-use service demands. Linking energy industries, processes, and geographies could lower costs, reduce environmental impacts, and increase the reliability of low-carbon energy systems.[75,220,221]

## *Potential Opportunities to Reduce Land-Related Emissions*

### Modern Foods

Recent innovations aim to increase food choices with plant-based and cultured meat[222,223,224] and foods synthesized chemically without photosynthetic inputs[225,226] that may be able to displace demand for foods with substantially higher emissions per calorie. However, the potential benefits will depend on the scalability and public demand for such products.

### Interventions to Reduce Methane and Nitrous Oxide Emissions

There are a number of options for reducing non-$CO_2$ GHG emissions from agriculture whose potential remains uncertain. Ruminant feed supplements may suppress methane emissions (although some such supplements have not yet been approved for use in the United States).[227,228] Methane from manure lagoons can be captured and used for bioenergy or reduced through flaring.[229] Seasonally flooded rice paddies can undergo temporary drainage to reduce emissions by about 40%.[230] And crops may be bred to produce root exudates that inhibit nitrification and thereby reduce $N_2O$ emissions from croplands.[231]

## Key Message 32.4

## Mitigation Can Be Sustainable, Healthy, and Fair

Large reductions in US greenhouse gas emissions could have substantial benefits for human health and well-being (*high confidence*). Mitigation is expected to affect pollution, the use of land and water resources, the labor force, and the affordability, reliability, and security of energy and food (*high confidence*). An equitable and sustainable transition to net-zero-emissions energy and food systems in the United States could help redress legacies of inequity, racism, and injustice while maximizing overall benefits to our economy and environment (*high confidence*).

A number of important dimensions rarely represented in mitigation scenarios may nonetheless determine the pace, feasibility, likelihood, efficacy, and cost-effectiveness of mitigation opportunities.

## *Air Pollution*

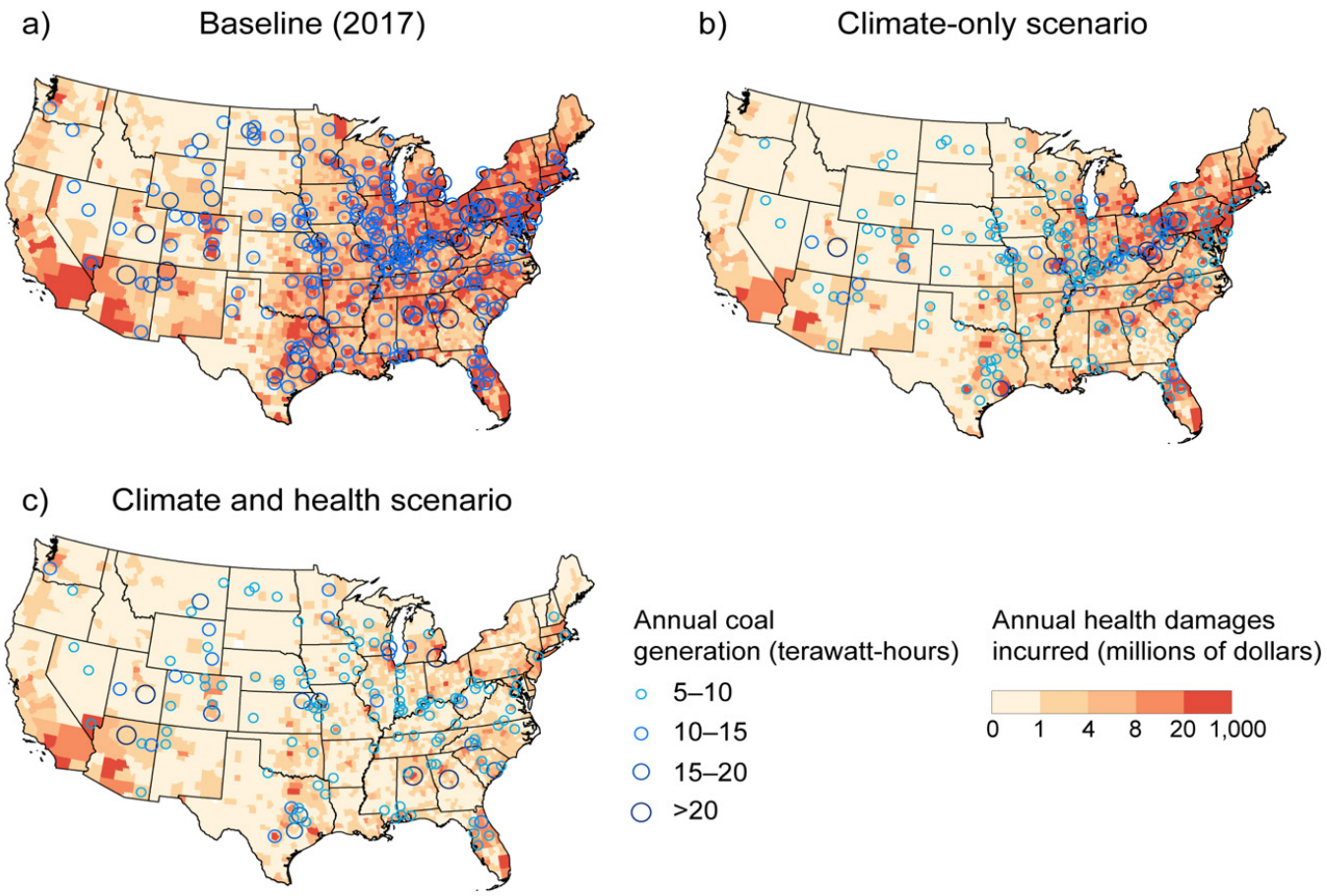
Air pollutants that impact human health are often co-emitted with greenhouse gases. Exposure to ambient fine particulate matter ($PM_{2.5}$) and ozone, which are among the largest risk factors for disease, causes 60,000–300,000 excess deaths per year in the United States (KM 14.5),[232,233,234,235,236,237,238] with health effects observed at concentrations below the current national standard.[239,240,241] Racial, ethnic, and socioeconomic disparities in air-pollution exposure are well documented[234,242,243,244,245,246,247] and have persisted despite overall decreases in air pollution.[234,240]

Transitioning to a net-zero-emissions energy system has the potential to generate substantial air pollution benefits. Estimates of cumulative net benefits by 2050 range from roughly 200,000 to 2,000,000 avoided deaths,[233,248,249,250] the monetized value (i.e., statistical value) of which could exceed the total expected costs of the transition to net zero.[49,251] However, the distribution and magnitude of air pollution benefits over the transition period depend on the pace of electrification, technology selection, and siting decisions,[49,252,253,254] especially regarding retirement of fossil fuel power plants (Figure 32.15)[254,255,256,257,258,259,260] and vehicle electrification.[261,262] Electrification of heating,[256,263] reduction in fossil fuel production, electrification of the industrial sector, and shifting diets[102] can also all generate meaningful air pollution benefits. Carbon

capture and hydrogen technologies may also reduce air pollutant emissions, although it is not yet clear by how much.

It is also possible that mitigation efforts could increase air pollution at local and regional scales, for example, due to increases in bioenergy, residential wood heating, and domestic manufacturing to meet demands for materials and products (e.g., Gallagher and Holloway 2020;[252] Commane and Schiferl 2022[264]).

## Health Co-benefits of Strategic Power Plant Retirements




**Shutting down coal-fired power plants would produce both health and climate benefits.**

**Figure 32.15.** Blue circles show the location and size of US coal-fired power plants in 2017 (**a**) and in two scenarios: one in which the fewest plants are retired to reduce $CO_2$ emissions by a fixed amount (**b**) and one in which plants are retired not only to achieve the same $CO_2$ reduction but also to avoid health damages as much as possible (**c**). Not surprisingly, estimated health damages (red shading) are greatly reduced in the future scenario that prioritizes health. Annual generation from coal power plants (in terawatt-hours) and corresponding annualized health damages (in millions of dollars) from each scenario are both summarized by county. Baseline shows results based on 2017 continuous emissions monitoring systems data, while optimization results shown represent the climate-only and climate-plus-health scenarios. Health damages are shown by the county in which those damages occur; legend breaks are based on quintiles of the data. Although this analysis included only the continental US, its conclusions are consistent with similar analyses in other regions: substantial health benefits would be expected from retiring coal electricity anywhere. Adapted with permission from Sergi et al. 2020.[254]

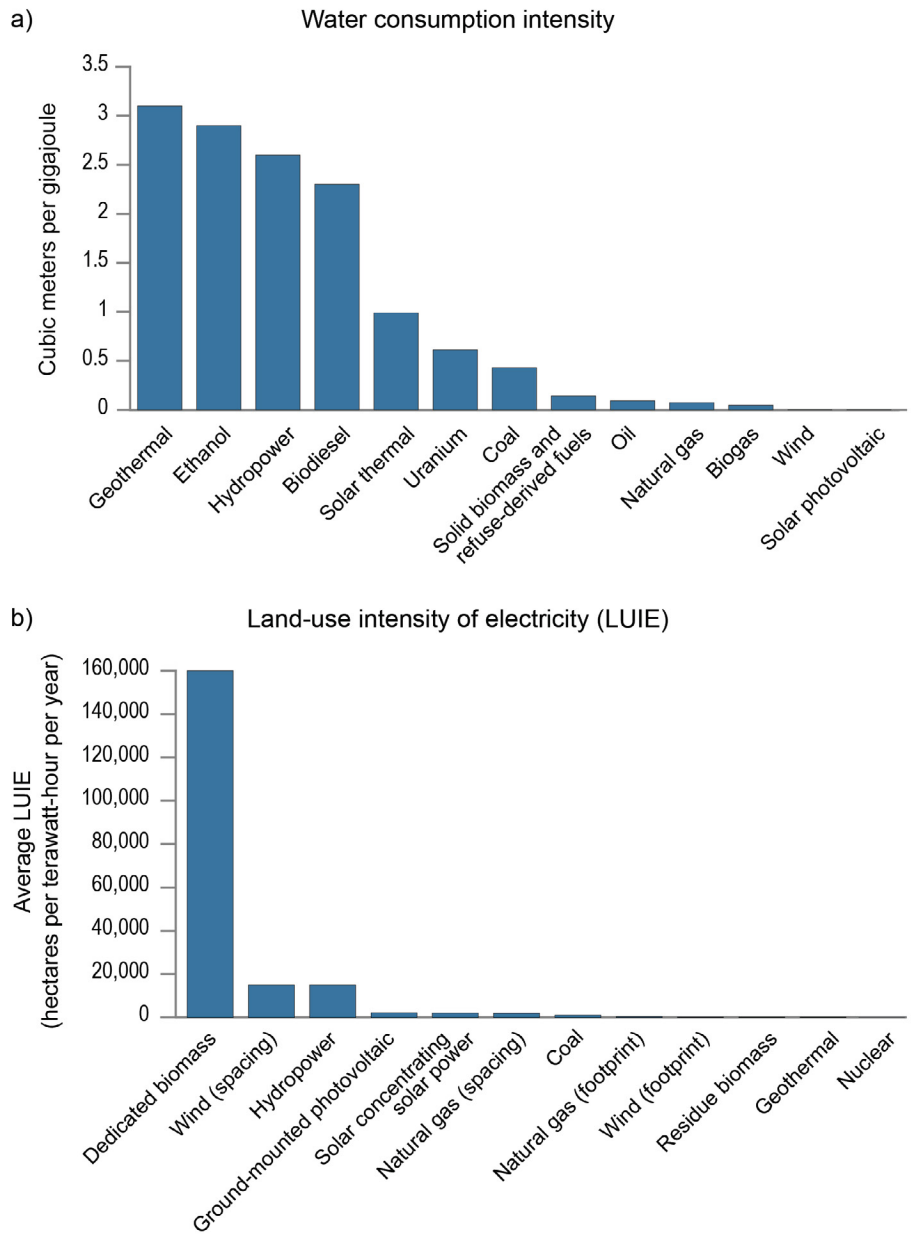
## Siting and Land Use

Net-zero-emissions energy systems may require large land areas, with land requirements in rough proportion to the share of wind and solar energy. Cumulative US land use for solar and wind energy in recent net-zero scenarios ranges from about 250,000 to more than 1 million square kilometers (including the entire area of solar and wind farms),[41,42,52] with solar concentrated in the Northeast and Southeast and wind in the Midwest, Great Plains, and Texas (KM 6.3).[49] Even at the low end of this range, the projected scale of land use is massive, and may face public opposition. For example, the visual impact and competition for land of such extensive systems would need to gain and maintain the support of many communities; this recently has been a challenge in the siting of solar and wind projects.[265,266] Similar challenges may apply to siting and demonstration of other infrastructure regardless of its land footprint, such as new electricity transmission,[265] CCS,[267] and CDR.[268] Others express concern over the potential environmental impacts of solar and wind farms, including land-cover change, loss of plant and animal habitats, barriers to migration and collision deaths of birds and bats,[269,270,271] and competition for land between agriculture and renewables.[272] Notably, competition with agriculture has also long been a concern about bioenergy, which may be alleviated if demand for corn ethanol decreases due to electrification of transport.[273,274] Researchers have thus begun developing pathways that take some of these concerns and constraints into account,[49,275] as well as identifying changes in governance and administrative law that may help streamline siting processes;[276] however, siting may prove a key obstacle for renewables-based net-zero-emissions systems.[277] Engagement with community groups and stakeholders early in the planning process has the potential to reduce project delays and cancellations.[278]

## Water Use

The water requirements of net-zero-emissions energy systems could be lower than current consumption,[279] largely because wind and solar require little water (Figure 32.16; KM 5.1).[280,281,282,283] However, some processes for energy conversion and carbon management, such as electrolysis for hydrogen production, chemical synthesis of hydrocarbons (e.g., by the Fischer-Tropsch process), and CCS, are water intensive and could offset water savings from fuel switching. Ultimately, water use (and related quality), temporal, and locational needs, depend heavily on the mix of resources and processes used to achieve net-zero emissions.[284,285,286]

## Land and Water Requirements of Energy Sources




**Different sources of energy entail more or less water and land use.**

**Figure 32.16.** Bars depict water-consumption intensity (**a**) and land-use intensity of electricity (LUIE) for the US in 2014 (**b**) related to different electricity sources. Wind and solar use less water than any of the other energy sources but more land area than nuclear, geothermal, or fossil sources. (a) Adapted with permission from Grubert and Sanders 2018;[280] (b) adapted from Lovering et al. 2022[287] [CC BY 4.0].

## *Labor*

The productivity, supply, and disposition of labor, in addition to national discourse and community-level support and concern regarding labor, has the potential to accelerate or constrain mitigation efforts. Nearly 8 million Americans were directly employed in energy-related jobs in 2021, comprising roughly 5% of the total labor force.[288,289] Of those 8 million energy-related jobs, approximately 41% were in net-zero-emissions-aligned areas in 2022.[290] Energy-related jobs tend to be geographically concentrated in certain states and

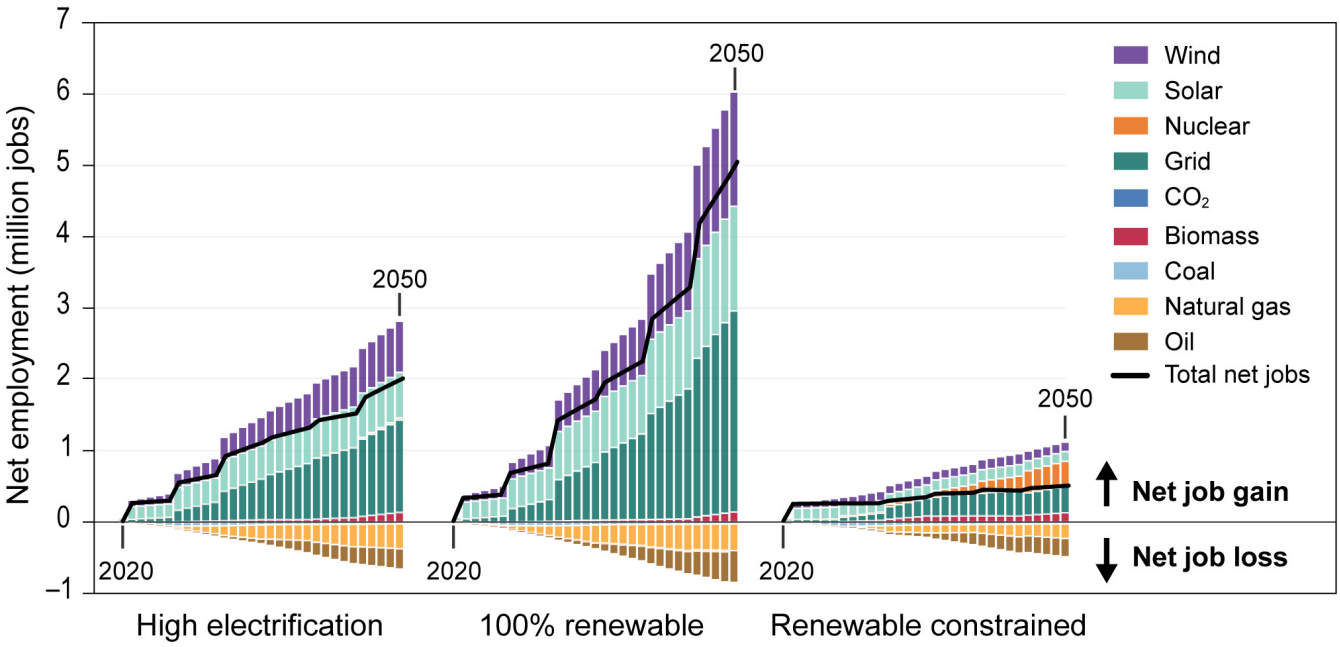
communities (Figure 32.17). More than 10% of the labor force in 150 counties (of 3,142) is directly employed in energy-related jobs[288,291,292]—often the production of coal, oil, and gas—but employment in mitigation-related activities is growing and is already high in many counties (e.g., energy efficiency in Vermont, wind installations in the Southern Great Plains; KM 26.2).

Reaching net-zero emissions in the United States by 2050 would generate jobs related to manufacturing and deployment of new infrastructure but reduce fossil fuel–related jobs.[293] Many analyses find that employment and wage losses in fossil fuel sectors would be entirely offset (in aggregate) by increases in low-carbon resource industries.[293,294,295,296,297] The number and local distribution of mitigation-related jobs will depend on the ultimate mix of energy sources, siting and investment decisions, labor supply constraints, the extent of domestic manufacturing, and political bargaining; however, decarbonization could lead to long-term expansion in the energy workforce in most states, even when accounting for increased worker productivity (which is often an underlying assumption in technology cost projections). Large-scale and sustained workforce development programs, high-road labor practices and policies, and corresponding federal support could accelerate a transition to net-zero emissions.[293,298]

However, there is already evidence of hiring difficulties in energy labor markets,[291] portending labor supply bottlenecks in the absence of counteracting policies. Although there is public support for employment benefits related to climate mitigation,[294] there is also evidence of mistrust associated with historical energy-related job creation narratives.[299] Moreover, there are existing racial and gender disparities in the energy workforces.[291]

Meanwhile, despite policy and political discourse regarding just transitions for fossil fuel workers,[294,300,301] many fossil fuel–dependent communities have experienced large declines in employment.[26,302,303] Moreover, former fossil fuel workers often relocate because their skills are not always transferable to other local industries, and nearby communities lose tax revenues that support public infrastructure and social services (KM 26.2).[304,305] Going forward, domestic policies that consider when and where workforces in declining energy industries could fill new jobs in emerging energy sectors (e.g., natural gas and carbon capture supply chains; coal mining; and solar manufacturing) have the potential to moderate labor supply bottlenecks, concentrated unemployment, and low-carbon boom-and-bust cycles. Where there is flexibility in siting of infrastructure and allocation of funding, such funds might also be leveraged to build political support and more equitably distribute costs and benefits. For example, provisions in the Inflation Reduction Act of 2022 offer enhanced tax credits to clean energy projects that pay prevailing wages to workers and use registered apprentices,[290] that manufacture and source materials domestically,[306] and/or that are located in "energy communities" defined by thresholds in the share of fossil fuel–related jobs.[307]

### Energy Employment from 2020 to 2050 for Alternative Net-Zero Pathways




**A shift toward renewables is projected to increase the total number of jobs in the energy sector.**

**Figure 32.17.** Despite decreases in the number of fossil fuel–related jobs, the overall number of energy jobs (specifically those involved in the supply of energy) is generally projected to increase in net-zero-emissions energy scenarios between 2020 and 2050, although by much more in some scenarios than in others. These particular scenarios are from Larson et al. 2021[49] and span a range of energy futures in which nearly all buildings and transport are electrified but there are no constraints (**a**), renewables produce 100% of energy (**b**), or renewables produce much less energy and nuclear and fossil energy with carbon capture and storage are prevalent (**c**). $CO_2$ = carbon dioxide. Adapted with permission from Jenkins et al. 2021.[308]

## *Energy Equity and Environmental Justice*

Social inequities in the United States are rooted in systemic discriminatory practices, such as redlining, that marginalize communities based on race or socioeconomics. Social equity involves several energy- and climate-related aspects of recognition, procedural, and distributional justice (KMs 23.4, 27.3).[309,310] In the context of energy and climate decision-making, recognition justice refers to an understanding that certain individuals and groups are presently bearing, and have historically borne, disparate burdens related to our collective energy systems and may therefore require extra resources or mitigation efforts. Procedural justice considers who is involved and has influence in energy and climate decision-making processes, with the goal of ensuring that those who want to be included in decision-making processes—and especially those who will be affected by the outcomes—are meaningfully engaged through fair and inclusive procedures (see, e.g., KM 30.3 regarding mitigation informed by Indigenous Knowledge). Distributional justice refers to the allocation of benefits and burdens based on geography and sociodemographics, with the objective that no single population receives a disproportionate share of energy or climate harms (e.g., energy-related air pollution; KM 14.3) or benefits (e.g., access to low-carbon and efficient energy technologies or clean-tech jobs).

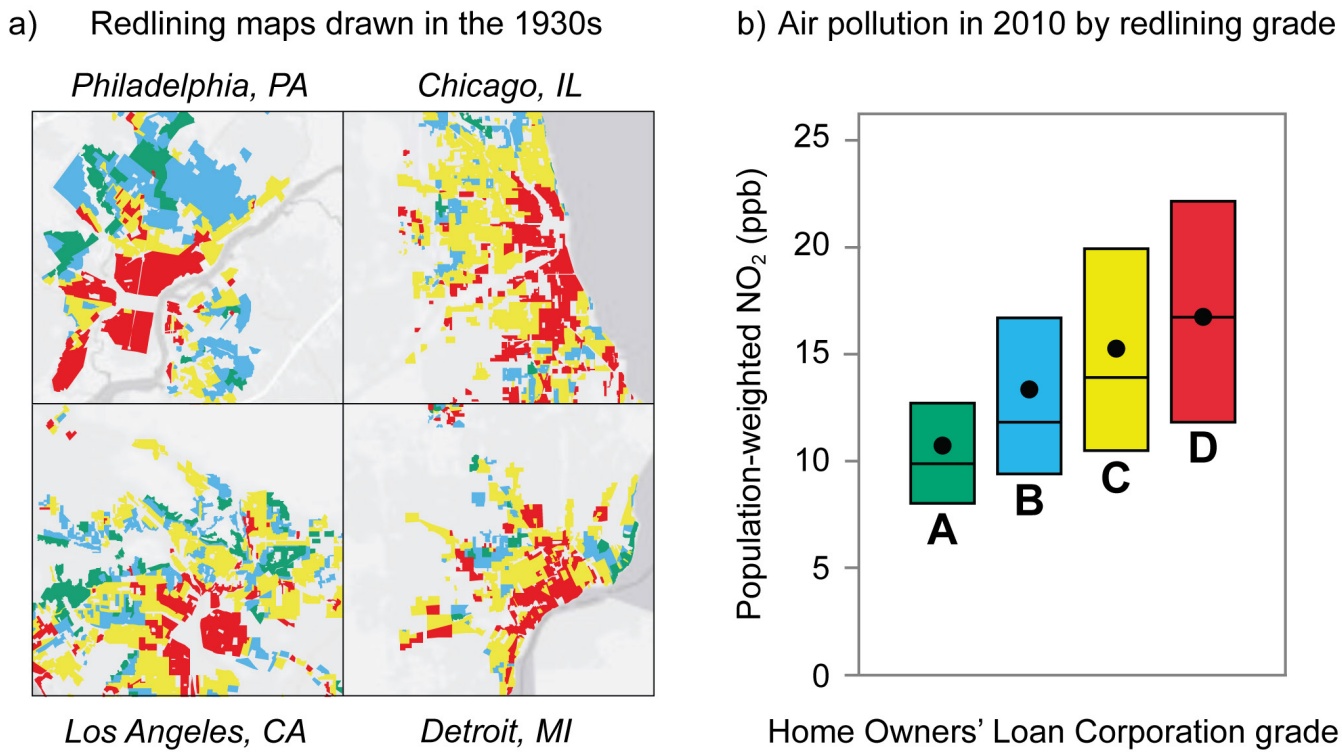
The disproportionate public health burdens of energy systems on communities of color and/or low-income communities, such as from vehicle emissions and power plants, have been extensively documented (Figure 32.18).[311,312,313,314] Energy insecurity (e.g., regularly struggling to pay energy bills) also disproportionately affects low-income households, communities of color, rural and Indigenous communities, families with children,

and older adults (Ch. 16).[313,315,316,317,318,319,320] This disproportionate burden of energy insecurity reflects that Black Americans, for example, are more likely to live in older homes that are less energy-efficient.[317,318,321] Moreover, redlined areas often lack trees and green spaces to mitigate the urban heat island effect and thus experience higher summer temperatures than surrounding urban areas,[322,323,324] which in turn increases energy demands and burdens[325] and makes residents more susceptible to the adverse health effects of extreme heat (KM 15.3).[325,326]

Although environmental impacts and energy insecurity are not borne proportionately across social groups, it is possible to pursue mitigation options that also redress current and historical injustices. For example, low-income communities and communities of color could experience disproportionate improvements in air pollution.[251,259] Energy equity considerations also include access to sufficient energy services,[327,328] as well as reductions in energy burden or energy poverty,[321,329,330] and the upfront costs of energy efficiency and low-carbon technologies.[331] Mitigation efforts that increase the availability and affordability of energy services (including safe and comfortable temperatures) could improve energy equity outcomes. For example, improving thermal efficiency of buildings would both reduce energy costs and help to maintain safe indoor thermal temperatures in the absence of functional air-conditioning.[332]

Studies have found that low-carbon and efficient technologies (e.g., electric vehicles, solar panels, battery storage, and LED lightbulbs) tend to be disproportionately owned by—and the financial incentives for such are received by—higher-income, more educated, and White households.[311,312,313,333] Job opportunities in clean energy have also tended to exclude women and people of color.[334] Moreover, insofar as mitigation increases energy costs, more households will experience energy poverty, and energy inequities may get worse.[335,336] In addition, changes in the type, timing, and cost of energy needed to provide safe and comfortable temperatures under climate change and anticipated electrification patterns may exacerbate health risks, financial energy burdens, and other measures of energy equity.[327,335]

## Inequitable Air Quality Within Historically Redlined Neighborhoods



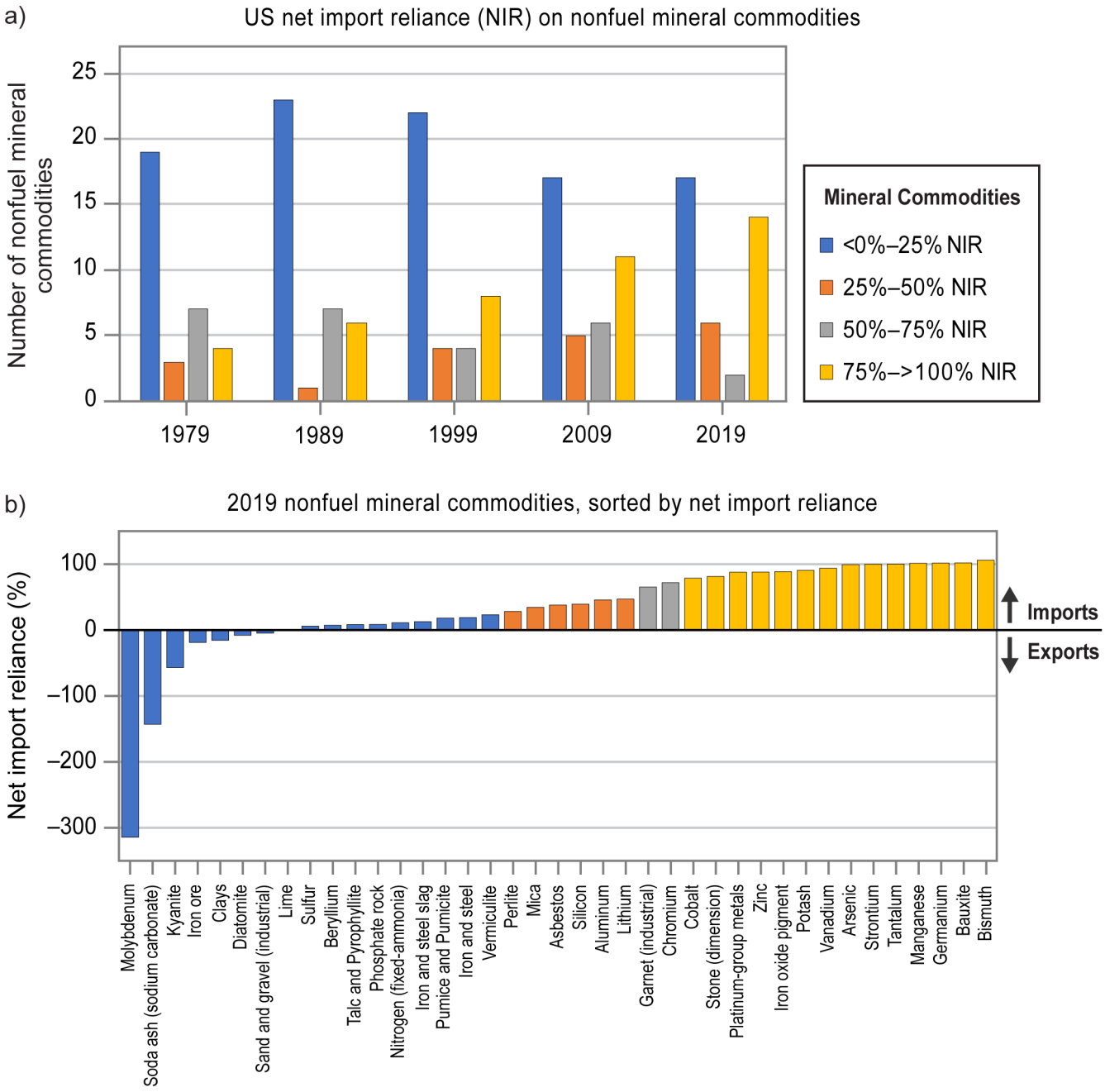

**Communities redlined in the 1930s experience more air pollution today.**

**Figure 32.18.** The Home Owners' Loan Corporation (HOLC) grades (A ["best"], B, C, and D ["hazardous," i.e., redlined]) from the 1930s (which effectively denied Black and minority groups access to lending institutions) still corresponded to greater levels of air pollution in 2010. Panel (**a**) shows redlining maps of neighborhoods based on 1930s HOLC grade classifications for four US cities. Panel (**b**) shows the population-weighted distribution of nitrogen dioxide ($NO_2$) levels (measured as concentration in parts per billion [ppb]) for 2010 across 202 census tracts in the contiguous US. Horizontal lines indicate medians, points indicate averages, and bars indicate 25th to 75th percentiles. Adapted with permission from Lane et al. 2022.[314]

## Supply Chains, Energy Security, and Geopolitics

Climate mitigation efforts may drastically increase domestic and global demand for products (e.g., solar photovoltaics, batteries, electric motors, wind turbines) and metal and mineral resources (e.g., lithium, nickel, cobalt, copper), which may have implications for supply security, markets, advanced manufacturing (e.g., robotics and EVs), geopolitics, and mining (Focus on Risks to Supply Chains).[337,338,339,340] Moreover, in the United States there are currently 50 listed critical minerals (up from 35 in 2018),[341,342] defined as those essential to economic or national security and whose supply chains are vulnerable to disruption (Figure 32.19). With increased demand as the system decarbonizes, there could be near-term shortages in several minerals and metals. Note that a series of executive orders anticipates this challenge and calls for monitoring and reduction in US dependence on imported critical materials, for example, by increased recycling (e.g., Executive Order 13817, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals,"[343] and Executive Order 13953, "Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries and Supporting the Domestic Mining and Processing Industries"[344]) and more resilient supply chains generally (Executive Order 14017, "America's Supply Chains";[345] see also Focus on Risks to Supply Chains; KMs 17.2, 18.1).

## Increasing Reliance on Imported Nonfuel Minerals




**The US has grown increasingly dependent on imported minerals.**

**Figure 32.19.** Panel (**a**) shows that the US has become increasingly dependent on imports of 39 nonfuel mineral commodities since 1979; commodities of which 75%–100% is imported (yellow bars) are increasing in number, and commodities of which less than 25% is imported (blue bars) are decreasing in number. Panel (**b**) shows the specific commodities and the degree of import reliance for each in 2019. Figure credits: (a) adapted from Fortier et al. 2015;[346] (b) University of California, Irvine.

## Key Message 32.5

## Governments, Organizations, and Individuals Can Act to Reduce Emissions

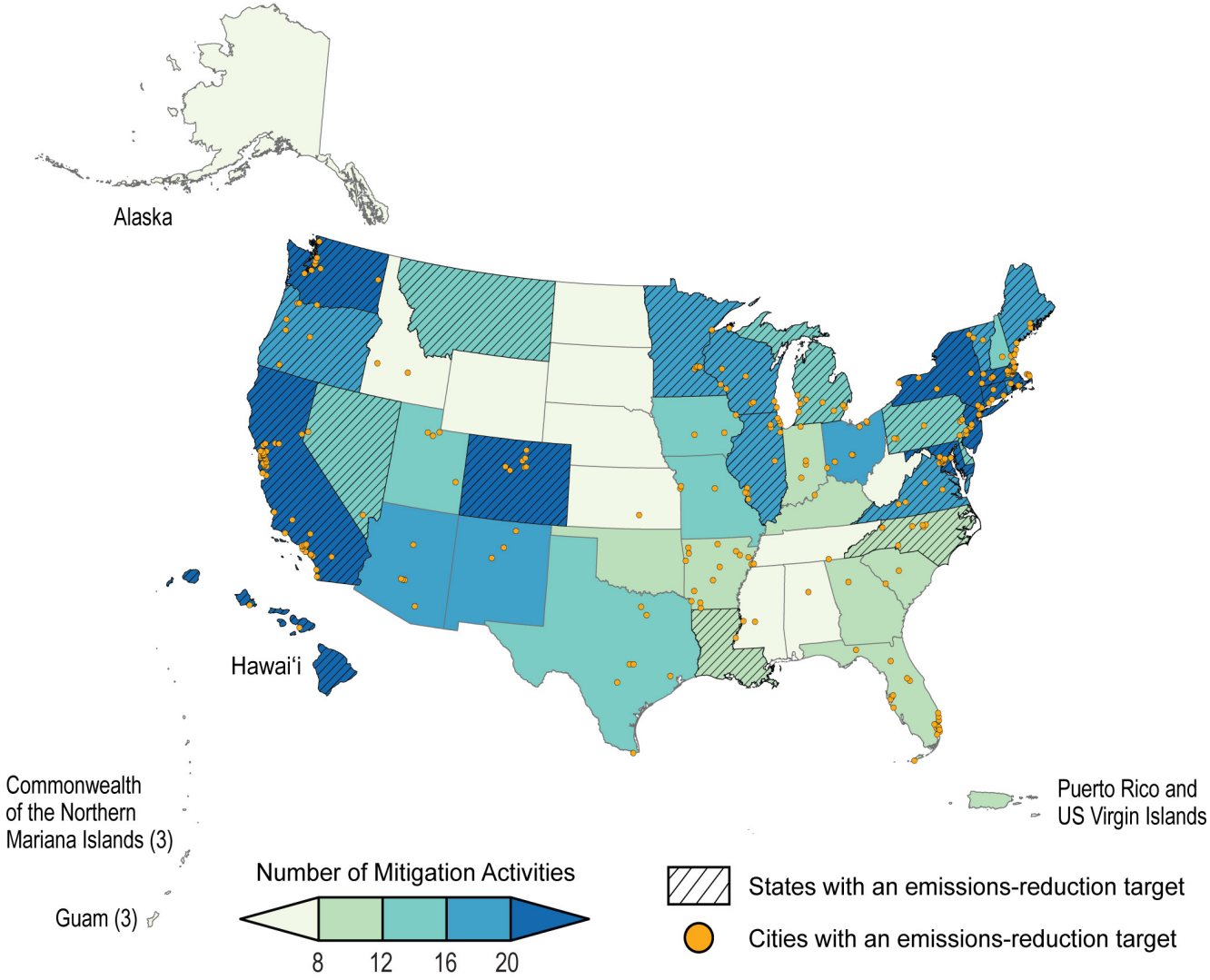
Mitigation efforts can be supported by a range of actors and actions, from choices made by individuals to decisions made by businesses and local, Tribal, state, and national governments (*high confidence*). Actions with significant near-term potential include sector-based policies accelerating deployment of low-carbon technologies, city-level efforts to promote public transportation and improve building efficiency, and individual behavioral changes to reduce energy demand and meat consumption (*high confidence*).

A wide range of actors across the US have been involved in efforts to accelerate clean energy transition and mitigate GHG emissions, including new legislation; rules, regulations, and executive orders; and voluntary actions. For example,

- the US has committed under the Paris Agreement to reduce GHG emissions by 50%–52% in 2030 relative to 2005;
- through the Bipartisan Infrastructure Law and the Inflation Reduction Act and relevant programs, there are federal subsidies to clean energy businesses and for household purchases of EVs and heat pumps;[347]
- 25 states,[348] 675 cities, 300 universities, and hundreds of companies have announced net-zero-emissions targets; and
- bottom-up coalitions such as the America Is All In initiative have support from subnational leaders who represent a constituency of more than half the US population (see, e.g., KMs 21.4, 30.3).

Since 2018, the total number of state-level mitigation activities has increased by 83%, and 169 more cities have introduced emissions reduction targets since then (Figure 32.20; see also Ch. 12).[349]

## Mitigation-Related Activities at the State and City Levels

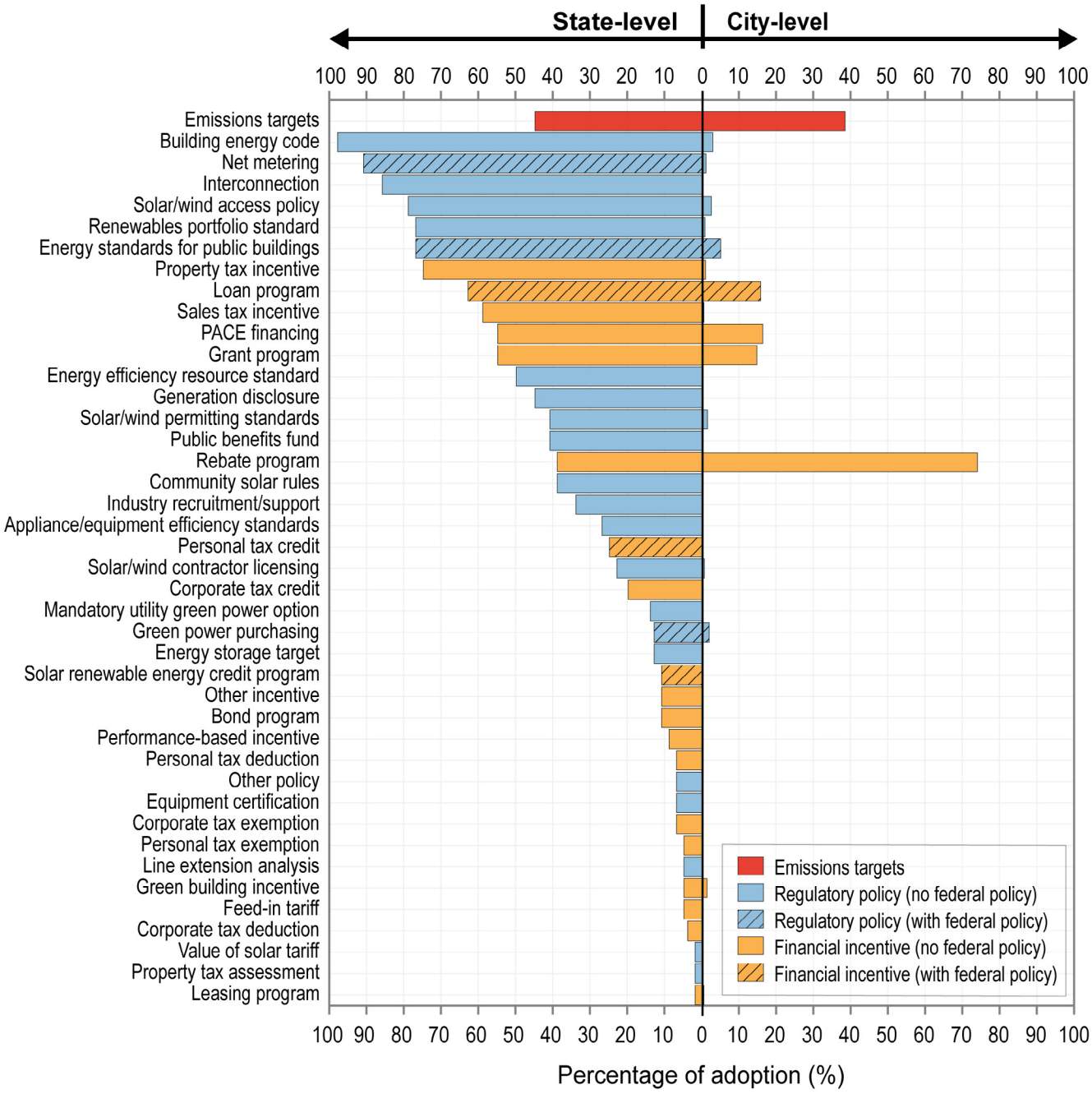



**Many states and cities have taken action to reduce greenhouse gas emissions.**

**Figure 32.20.** Shading indicates the number of mitigation activities taken by each state, and orange circles indicate cities with emissions-reduction targets (as of April 2023). Almost every region has taken some action, with hotspots of activity in the Northeast, Southwest, Colorado, Hawai'i, and along the West Coast. See Figure 32.21 for examples of the types of actions taken. Figure credit: The Pennsylvania State University, NOAA NCEI, and CISESS NC.

The pathways toward achieving these goals often include a broad collection of measures and policies, including investments in infrastructure and clean technologies that will require substantial capital, financial backing, and resource allocation. The feasibility and impact of these measures are dependent on local and regional factors, which are often reflected in more granular sector- or economy-specific mitigation targets and actions (see Figure 32.21).[350]

## Adoption Rate of Various Forms of Policy Instruments and Climate Action




**States and cities have adopted a range of climate actions and policies.**

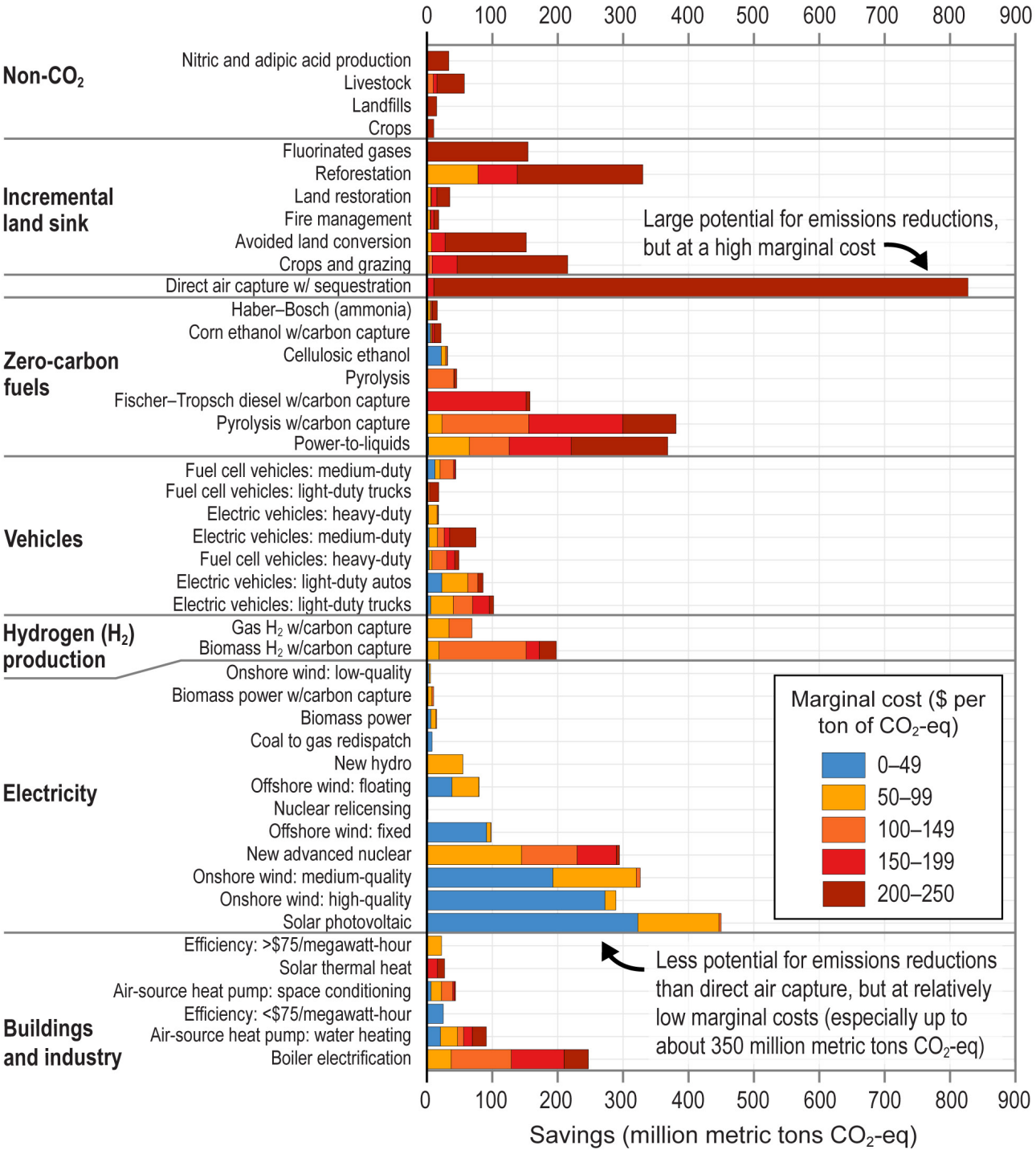
**Figure 32.21.** Bars show the percentages of states (**left**) and cities (**right**) that have announced emissions targets (tracked by the United Nations Framework Convention on Climate Change Non-state Actor Zone for Climate Action dataset) or adopted the selected clean energy policies (tracked in North Carolina State University's Database of State Incentives for Renewables & Efficiency dataset) as of April 2023. The color of the bars indicates the type of policy, and hashing denotes that the policy action is also being adopted or announced by the Federal Government. PACE stands for property assessed clean energy. Figure credit: The Pennsylvania State University, NOAA NCEI, and CISESS NC.

To this end, nearly 40 states have introduced renewable portfolio standards or voluntary renewable energy goals, which further guide and codify decarbonization efforts within the energy sector and induce incremental shifts toward increased penetration of renewable electricity (KM 32.1). Similarly, more than 30 local governments have enacted requirements for energy efficiency, ranging from building codes and benchmarking ordinances to establishing performance standards (see, e.g., KM 12.3). With federal corporate average fuel economy (CAFE) standards in place for vehicles, local transportation-sector efforts are often focused on behavioral mode-shift goals, such as promoting clean and public transport options and reducing vehicle-miles traveled. The proposed federal Agriculture Resilience Act is designed to address the adaptive needs of US farmers and consumers as a result of a changing climate, as well as to reduce the emissions associated with agricultural production.[351] In addition, the Securities and Exchange Commission is in the process of finalizing new rules that would require public companies to disclose greenhouse gas emissions related to their operations and supply chains, as well as climate risks to their business.[352] Such rules would build on the voluntary reporting and reduction efforts of corporations under the Carbon Disclosure Project; Science Based Targets initiative; and Environmental, Social, and Corporate Governance frameworks and will need to be supported by improved accounting protocols and focused scientific research.[174,353,354,355,356]

Beyond goal-setting and implementing regulatory measures, the enabling of financial mechanisms is often a core element of mitigation strategy. Regional cap-and-trade programs utilize a system of accountability and performance to incentivize emissions reductions at the electricity-generation level. Meanwhile, federal subsidies, such as those provided to clean energy businesses and tax credits for electric vehicle purchases, can bolster behavior change.[54] By enabling access to financial capital—whether within the government, commercial, or residential sectors—investments in infrastructure and the built environment, as well as research and development, may further drive these advances.

Available mitigation strategies vary in terms of emissions-reduction potential and costs (Figure 32.22), as well as in environmental, technical, and social implications (Figure 32.23). However, with the advancement of measurement technologies and insights gained from the deployment of various actions taken in vastly different environments, there is now more empirical evidence to inform strategy design for a given community (see regional chapters for examples of state, city, community, and Tribal mitigation actions; e.g., Box 21.1; KM 30.3). Additionally, more jurisdictions are adopting community-driven and holistic approaches to climate action planning, incorporating practices that address equitable access to information (including considerations for languages used and internet access) and events (including transportation vouchers, food and childcare provisions, and payment for subject-matter expertise to community members with lived experience), with a goal of improving and increasing capacity and ability to influence decision-making and, ultimately, assisting elected leaders in making the best-informed and most-impactful decisions for their unique communities.[357,358,359]

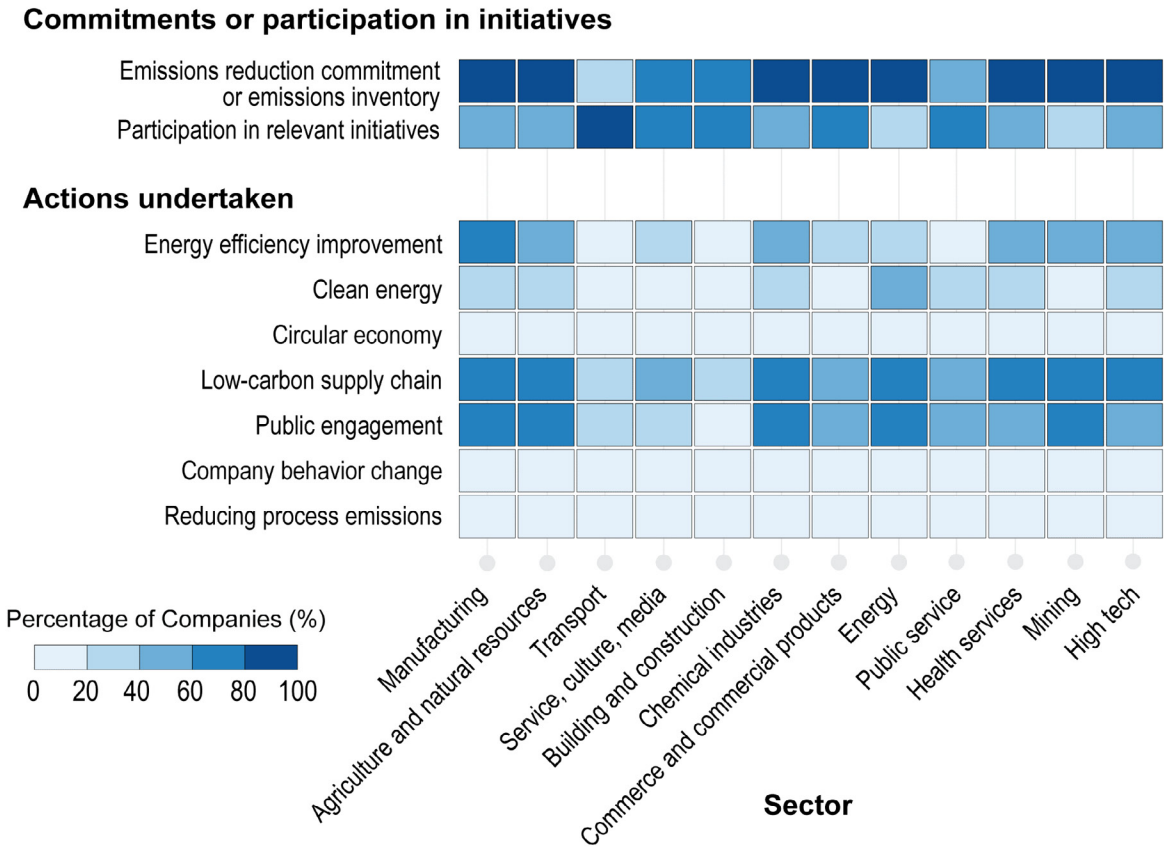
## Potential Emissions Reductions by Action, for the Year 2050




**The size and cost of emissions reductions depend on available technologies and the source of related emissions.**

**Figure 32.22.** Energy system, land-sector, and non-$CO_2$ (carbon dioxide) mitigation options for the year 2050 are shown along with estimated marginal costs, excluding the impact of policy incentives. The sum of the mitigation options shown results in net-negative $CO_2$-eq (carbon dioxide equivalent) emissions in the United States, not only demonstrating the possibility of reaching net-zero emissions using a combination of these actions but also highlighting a large range of costs for such actions (costs as of 2021). Mitigation options from conservation and lifestyle change are not assessed due to the difficulty in assessing costs for these measures. $H_2$ = hydrogen. Adapted with permission from Farbes et al. 2021[360] and Figure SPM.7 in IPCC 2022.[361]

## US Company-Level Mitigation Actions




**A majority of US companies have made mitigation commitments, inventoried emissions, or participated in initiatives, but fewer are taking action.**

**Figure 32.23.** As of April 2023, a majority of US companies across many sectors have committed to reducing emissions or conducted emissions inventories, and many have participated in mitigation initiatives (**top**). Percentages are smaller in terms of actions taken (**bottom**). For example, many companies are involved in energy efficiency improvements, efforts to reduce supply chain emissions, and public engagement efforts. But 20% or fewer across all sectors are reported as reducing process emissions or effecting company behavior changes. Figure credit: The Pennsylvania State University, NOAA NCEI, and CISESS NC.

## Box 32.3. Orlando Case Study: Mitigation in the Country's Most Visited City

In the five decades since the opening of Walt Disney World, Orlando has become the most highly visited city in the United States. As a result, this community faces the unique challenge of managing the costs, demands, and emissions of more than 75 million annual visitors, or nearly 300 visitors for each individual resident.[362,363] To address these impacts, local governments have adopted an ambitious, socially inclusive, and innovative climate strategy.

The prevalence of resort and multifamily developments, for example, has led to the adoption of energy efficiency requirements for commercial buildings and a community-wide commitment to 100% renewable energy to drive the decarbonization of the local building stock. Meanwhile, to address the needs of local residents, many of whom work in lower-wage jobs associated with the tourism industry, an energy-burden analysis was conducted to identify the neighborhoods most in need of assistance.

As the largest rental car market in the world, the region has served as a proving ground for enhanced electric and autonomous vehicle piloting,[364,365] as well as the adoption of an electric vehicle readiness policy.[366] Research efforts have focused on public safety when various modes of transportation, such as single-passenger vehicles (more likely to be utilized by visitors and more affluent residents), are active in the same vicinity as buses, cyclists, and pedestrians.

Enhanced waste-reduction efforts previously included an anaerobic digestion facility that utilizes the gray water and food scraps from the Disney parks and resorts to generate biogas, a renewable energy source that is used to power these same facilities. In tandem with this localized solution, waste avoidance and gleaning programs (e.g., improved collection of excess produce and perishables from farms, retailers, and restaurants)[367] provide options for those who are food insecure.

Together, these mitigation strategies serve to protect the local environment, enhance the quality of life for local residents, and showcase a variety of solutions to the nearly 76 million guests who visit the region each year.

# Traceable Accounts

## *Process Description*

Based on their own experience, nominations, and relevant recent literature, the chapter lead author and federal coordinating lead author discussed and selected a set of experts to invite as authors, seeking diverse representation of topical expertise, disciplinary perspectives, career stages, professional backgrounds, geographies, and demographics. Of 25 invitations, 16 were accepted, forming an author team with the requisite expertise to cover the chapter topics and provide a good balance of other characteristics. The author team began meeting regularly as a group and then divided into smaller working groups focused on different key topic areas, which also met regularly (all meetings were virtual, except for the in-person All-Author Meeting held in Washington, DC, in April 2023). During these meetings, the team worked together to develop key topic areas for the chapter, identify key literature and sources, and plan syntheses and figures for the chapter. The team also planned the public engagement workshop for the chapter and afterward discussed inputs and feedbacks from that workshop.

## Key Message 32.1

## Successful Mitigation Means Reaching Net-Zero Emissions

### Description of Evidence Base

The assessment and summary of the sources and trends of US greenhouse gas emissions relies primarily on inventories and estimates from the EPA,[7,8] supplemented by socioeconomic, energy activity, and agricultural production data from official sources such as the US Energy Information Administration (EIA)[18,368,369,370,371] and the World Bank.[372,373] EPA estimates of energy-related emissions are primarily based on tracked masses and volumes of combusted fuels (and in some case continuous emissions monitoring at point sources) publicly reported to the EIA, EPA, or Bureau of Transportation Statistics. EPA estimates of land sector (i.e., land use, land-use change, and agricultural) emissions are primarily based on activity data (e.g., area of land converted, number and kinds of livestock, mass of fertilizer applied) and associated emissions factors that have been developed based on numerous case studies.[11,374] Federal- and state-level greenhouse gases (GHG) targets were compiled from publicly available sources and are not uncertain.

### Major Uncertainties and Research Gaps

Although there is no uncertainty as to the current emissions targets and it is well-established that global warming will be proportional to cumulative carbon dioxide ($CO_2$) emissions (e.g., Matthews et al. 2009[375]), there is relatively little scientific literature and relatively few national and international goals that address long-term management of the climate after net-zero emissions have been achieved and into the 22nd century.[376]

Estimates of agricultural and fugitive non-$CO_2$ GHG emissions have greater uncertainty because they are spatially heterogenous "area" sources that are more challenging to measure directly,[97,377] as evidenced by discrepancies between "top-down" estimates of global methane emissions based on measurements of the atmosphere and "bottom-up" estimates based on activity data such as number and kinds of livestock and extent of rice cultivation.[378,379] For this reason, these are active areas of research, and analysts are bringing to bear a variety of different and innovative tools and methods to reduce the uncertainty and prioritize mitigation efforts (e.g., Liu et al. 2022;[380] Norooz Oliaee et al. 2022;[381] Conrad et al. 2023[382]).

### Description of Confidence and Likelihood

Based on the multiple sources of high-quality energy system data, the authors have *very high confidence* in both the overall magnitude of energy-related US GHG emissions from each major source and their relative changes over time. There is also broad agreement among dynamic vegetation models, bookkeeping models of land-use change, and atmospheric observations as to the magnitude of the US land sink in recent years,[51] but the sink has been decreasing[22] and future uptake by US forests will depend on management and climate change impacts, both of which are uncertain.[21,180,383,384] Given current emissions levels and stated goals, however, the required rate of decrease is not in question. For these reasons, we have *very high confidence* in the statements made in the Key Message.

## Key Message 32.2

## We Know How to Drastically Reduce Emissions

### Description of Evidence Base

The assessment of established options for reducing energy-related GHG emissions reflects a large body of literature and recent energy-system modeling,[60,385] including a database of 40 US net-zero emissions scenarios.[41,42] Although there are substantial differences in the cost-effective energy systems modeled in these scenarios depending on model design and key assumptions, the Key Message and text emphasize characteristics that are robust across most, if not all, of the scenarios.[47,50,130,386,387,388]

### Major Uncertainties and Research Gaps

The assessment of established options for reducing land-related GHG emissions reflects a substantial literature, but there are few quantitative scenarios to support potential reductions.[96,98,121,177,185,191,389,390,391] Instead, potential reductions are often extrapolated from the localized studies that are available. Further research is warranted to test key sensitivities in energy model scenarios and to quantitatively assess factors beyond cost, such as social and political acceptance of (or opposition to) changes in use of land and water resources and adoption of energy technologies, and the associated distribution of benefits and impacts (as well as other non-cost factors discussed in KM 32.4).

### Description of Confidence and Likelihood

Across 40 of the most recent and detailed energy system scenarios of net-zero US emissions, produced by 14 independent models and assuming a wide range of costs and constraints, the share of final energy met by electricity increases from about 20% today to 43%–57% by 2050 (the 25th–75th percentile range; Figure 32.11), and solar and wind are consistently major sources of energy, typically ranging from 57%–80% of primary energy by 2050 (the 25th–75th percentile range; Figure 32.10). Yet fuels continue to be used across those scenarios for some transportation and industry applications. The robustness of these numbers despite many methodological differences gives us *high confidence* in the energy-related statements in the Key Message.

A large literature also supports the opportunities for large reductions in land-related emissions, giving us *high confidence* in the land-related statement in the Key Message.[96,98,121,177,185,191,389,390,391]

Current costs of technologies such as solar, wind, and electric vehicles and the projected large-scale deployment of these technologies in cost-optimized energy system models,[41,42,45,66,392] as well as many studies demonstrating the potential cost savings of energy efficiency improvements,[393,394] optimization of agricultural inputs,[395] shifts in diet,[96,98,396] and repair of leaky infrastructure, all give the authors similarly *high confidence* that many mitigation options are now cost-effective.

## Key Message 32.3

## To Reach Net-Zero Emissions, Additional Mitigation Options Need to Be Explored

### Description of Evidence Base

The assessment of potential options for reducing energy-related GHG emissions reflects a large body of literature and recent energy system modeling, including a database of 40 US net-zero emissions scenarios,[41,42] but this Key Message highlights that the scale and mix of energy technologies and mitigation options remain sensitive to assumed—and yet uncertain—costs and constraints. Similarly, the potential options for reducing land-related GHG emissions presented in this Key Message are not as well studied, and there is open debate about the efficacy and/or cost-effectiveness of, for example, different energy storage technologies,[397,398] advanced nuclear technology,[399,400] and carbon management options,[52,168,401,402] as well as future agricultural productivity.[403,404]

### Major Uncertainties and Research Gaps

We assign *medium confidence* to the list of attractive targets for further research, development, and demonstration because existing literature either disagrees as to the potential of these technologies or only a few studies have made the case that they have great potential. Where analyses disagree, it may be because their findings depend on assumptions regarding deeply uncertain aspects of economic development, human behavior, or technological innovation. In general, additional research is needed to quantitatively assess a greater number of emerging energy technologies and land management options, and especially work that incorporates the various non-cost factors discussed in Key Message 32.4.

### Description of Confidence and Likelihood

We have *high confidence* that we do not yet know which net-zero-emissions energy system will be cost-optimal (or socially and politically acceptable) and that we do not know the ideal types or scales of carbon management to support net-zero emissions and sustainability more broadly.[405,406] This is because there is substantial variation in the type and scale of energy and carbon management technologies deployed in model scenarios, long-term projections of technology costs span large ranges, and the social and political support for different mitigation efforts is unclear. Although the effectiveness and scalability of some of the approaches to reduce land-related non-$CO_2$ emissions remain uncertain (e.g., soil amendments, livestock feed supplements), other options are becoming clear, such as managing manure, cover cropping, and decreasing nitrogen fertilizer applications. Thus, we have *medium confidence* as to the options for reducing these land-related non-$CO_2$ emissions.

## Key Message 32.4

## Mitigation Can Be Sustainable, Healthy, and Fair

### Description of Evidence Base

The assessment of historical and future impacts of energy systems on, for example, water,[279,280,283,284] air pollution,[102,234,245,246,253,254] energy security,[31,339] labor,[233,247,293,298,305] and energy equity and environmental justice[217,251,259,300,309,329] is based on a diverse and rapidly growing academic literature as cited in the chapter.

### Major Uncertainties and Research Gaps

As mentioned in regard to other Key Messages, there is a lack of specific qualitative and quantitative analyses and decision-making tools regarding how mitigation may affect and be affected by energy equity, environmental justice, land use, labor, water, air pollution, and energy security in different places, times, and social, demographic, and political contexts (Carley, Evans et al. 2018). There is also a lack of analyses and tools to reflect interacting technological, social, political, and environmental uncertainties and choices to inform multistakeholder decision-making.[407]

### Description of Confidence and Likelihood

An extensive literature demonstrates the potential health benefits of climate mitigation, especially in regard to related decreases in air pollution. Fewer but still numerous studies have shown that the cost and resource savings or net social benefits of many mitigation options can accrue to specific populations. We therefore have *high confidence* in the potential benefits to human health and well-being, including specific environmental and socioeconomic effects. However, the available research also gives us *high confidence* that the benefits of mitigation may be distributed unevenly in the absence of proactive efforts to ensure fairness.

## Key Message 32.5

## Governments, Organizations, and Individuals Can Act to Reduce Emissions

### Description of Evidence Base

Our assessment of possible actors and mitigation actions is drawn from both the actions represented in models and studies by researchers,[408,409,410,411,412] as well as reports and databases that have compiled lists of past actions taken (e.g., the Center for Climate and Energy Solutions State Climate Policy Maps,[348] North Carolina State University Database of State Incentives for Renewables & Efficiency,[413] CDP States and Regions Climate Tracker,[414] and United Nations Framework Convention on Climate Change Non-state Actor Zone for Climate Action dataset[415]).

### Major Uncertainties and Research Gaps

No jurisdiction has yet transitioned from a fossil-based economy to a deeply decarbonized or net-zero-emissions one. Moreover, actions to start down that road may be different from those that reach the end of it.[416,417] Future research may productively explore the limits of actions by certain groups or jurisdictions, and seek to assess where collaborations are necessary and most valuable to support mitigation.[417,418]

### Description of Confidence and Likelihood

Public commitments made and actions already taken (as tracked by the sources cited in the evidence base above) give us *high confidence* that mitigation can be supported by a wide range of actors in a wide variety of ways. Historical progress in reducing emissions (e.g., US electricity emissions since 2007) and forward-looking modeling analyses give us similarly *high confidence* that substantial near-term potential in the US lies in actions to boost low-carbon technologies,[50,255,387,419,420,421] moderate use of internal combustion vehicles,[65,66,68] improved building efficiency,[32,33] and diet shifts.[96,98,396]

# References


1. Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld, 2021: Technical summary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 33–144. https://doi.org/10.1017/9781009157896.002

2. IPCC, 2022: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926

3. Feijoo, F., G. Iyer, M. Binsted, and J. Edmonds, 2020: US energy system transitions under cumulative emissions budgets. *Climatic Change*, **162** (4), 1947–1963. https://doi.org/10.1007/s10584-020-02670-0

4. Schaeffer, R., A. Köberle, H.L. van Soest, C. Bertram, G. Luderer, K. Riahi, V. Krey, D.P. van Vuuren, E. Kriegler, S. Fujimori, W. Chen, C. He, Z. Vrontisi, S. Vishwanathan, A. Garg, R. Mathur, S. Shekhar, K. Oshiro, F. Ueckerdt, G. Safonov, G. Iyer, K. Gi, and V. Potashnikov, 2020: Comparing transformation pathways across major economies. *Climatic Change*, **162** (4), 1787–1803. https://doi.org/10.1007/s10584-020-02837-9

5. van Soest, H.L., M.G.J. den Elzen, and D.P. van Vuuren, 2021: Net-zero emission targets for major emitting countries consistent with the Paris Agreement. *Nature Communications*, **12** (1), 2140. https://doi.org/10.1038/s41467-021-22294-x

6. DOS and EOP, 2021: The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. U.S. Department of State and U.S. Executive Office of the President, Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2021/10/us-long-term-strategy.pdf

7. EPA, 2022: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020. EPA 430-R-22-003. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020

8. EPA, 2023: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021. EPA 430-R-23-002. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021

9. Davis, S.J., Z. Liu, Z. Deng, B. Zhu, P. Ke, T. Sun, R. Guo, C. Hong, B. Zheng, Y. Wang, O. Boucher, P. Gentine, and P. Ciais, 2022: Emissions rebound from the COVID-19 pandemic. *Nature Climate Change*, **12** (5), 412–414. https://doi.org/10.1038/s41558-022-01332-6

10. Liu, Z., P. Ciais, Z. Deng, S.J. Davis, B. Zheng, Y. Wang, D. Cui, B. Zhu, X. Dou, P. Ke, T. Sun, R. Guo, H. Zhong, O. Boucher, F.-M. Bréon, C. Lu, R. Guo, J. Xue, E. Boucher, K. Tanaka, and F. Chevallier, 2020: Carbon Monitor, a near-real-time daily dataset of global $CO_2$ emission from fossil fuel and cement production. *Scientific Data*, **7** (1), 392. https://doi.org/10.1038/s41597-020-00708-7

11. IPCC, 2006: *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Eggleston, S., L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, Eds. Institute for Global Environmental Strategies, Hayama, Japan. https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

12. Crippa, M., D. Guizzardi, E. Pisoni, E. Solazzo, A. Guion, M. Muntean, A. Florczyk, M. Schiavina, M. Melchiorri, and A.F. Hutfilter, 2021: Global anthropogenic emissions in urban areas: patterns, trends, and challenges. *Environmental Research Letters*, **16** (7), 074033. https://doi.org/10.1088/1748-9326/ac00e2

13. Friedlingstein, P., M. O'Sullivan, M.W. Jones, R.M. Andrew, L. Gregor, et al., 2022: Global carbon budget 2022. *Earth System Science Data*, **14** (11), 4811–4900. https://doi.org/10.5194/essd-14-4811-2022

14. IEA, 2023: Greenhouse Gas Emissions from Energy. International Energy Agency. https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy

15. Liu, Z., P. Ciais, Z. Deng, R. Lei, S.J. Davis, S. Feng, B. Zheng, D. Cui, X. Dou, B. Zhu, R. Guo, P. Ke, T. Sun, C. Lu, P. He, Y. Wang, X. Yue, Y. Wang, Y. Lei, H. Zhou, Z. Cai, Y. Wu, R. Guo, T. Han, J. Xue, O. Boucher, E. Boucher, F. Chevallier, K. Tanaka, Y. Wei, H. Zhong, C. Kang, N. Zhang, B. Chen, F. Xi, M. Liu, F.-M. Bréon, Y. Lu, Q. Zhang, D. Guan, P. Gong, D.M. Kammen, K. He, and H.J. Schellnhuber, 2020: Near-real-time monitoring of global $CO_2$ emissions reveals the effects of the COVID-19 pandemic. *Nature Communications*, **11** (1), 5172. https://doi.org/10.1038/s41467-020-18922-7

16. Feng, K., S.J. Davis, L. Sun, and K. Hubacek, 2015: Drivers of the US $CO_2$ emissions 1997–2013. *Nature Communications*, **6** (1), 7714. https://doi.org/10.1038/ncomms8714

17. Scott Institute for Energy Innovation, 2017: Power Sector Carbon Index. Carnegie Mellon University, Pittsburgh, PA. https://www.emissionsindex.org

18. 1EIA, 2015: Residential Energy Consumption Survey. U.S. Energy Information Administration. https://www.eia.gov/consumption/residential/data/2015/

19. Goldstein, B., D. Gounaridis, and J.P. Newell, 2020: The carbon footprint of household energy use in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (32), 19122–19130. https://doi.org/10.1073/pnas.1922205117

20. Anderegg, W.R.L., O.S. Chegwidden, G. Badgley, Anna T. Trugman, D. Cullenward, J.T. Abatzoglou, Jeffrey A. Hicke, J. Freeman, and J.J. Hamman, 2022: Future climate risks from stress, insects and fire across US forests. *Ecology Letters*, **25** (6), 1510–1520. https://doi.org/10.1111/ele.14018

21. Domke, G.M., S.N. Oswalt, B.F. Walters, and R.S. Morin, 2020: Tree planting has the potential to increase carbon sequestration capacity of forests in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (40), 24649–24651. https://doi.org/10.1073/pnas.2010840117

22. Quirion, B.R., G.M. Domke, B.F. Walters, G.M. Lovett, J.E. Fargione, L. Greenwood, K. Serbesoff-King, J.M. Randall, and S. Fei, 2021: Insect and disease disturbances correlate with reduced carbon sequestration in forests of the contiguous United States. *Frontiers in Forests and Global Change*, **4**, 716582. https://doi.org/10.3389/ffgc.2021.716582

23. Lopez, A., B. Roberts, D. Heimiller, N. Blair, and G. Porro, 2012: U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis. NREL/TP-6A20-51946. U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO. https://www.nrel.gov/docs/fy12osti/51946.pdf

24. Shaner, M.R., S.J. Davis, N.S. Lewis, and K. Caldeira, 2018: Geophysical constraints on the reliability of solar and wind power in the United States. *Energy and Environmental Science*, **11** (4), 914–925. https://doi.org/10.1039/c7ee03029k

25. Olson-Hazboun, S.K., P.D. Howe, and A. Leiserowitz, 2018: The influence of extractive activities on public support for renewable energy policy. *Energy Policy*, **123**, 117–126. https://doi.org/10.1016/j.enpol.2018.08.044

26. Grubert, E., 2020: Fossil electricity retirement deadlines for a just transition. *Science*, **370** (6521), 1171–1173. https://doi.org/10.1126/science.abe0375

27. Shearer, C., D. Tong, R. Fofrich, and S.J. Davis, 2020: Committed emissions of the U.S. power sector, 2000–2018. *AGU Advances*, **1** (3), e2020AV000162. https://doi.org/10.1029/2020av000162

28. Tong, D., D.J. Farnham, L. Duan, Q. Zhang, N.S. Lewis, K. Caldeira, and S.J. Davis, 2021: Geophysical constraints on the reliability of solar and wind power worldwide. *Nature Communications*, **12** (1), 6146. https://doi.org/10.1038/s41467-021-26355-z

29. Stokes, L.C. and H.L. Breetz, 2018: Politics in the U.S. energy transition: Case studies of solar, wind, biofuels and electric vehicles policy. *Energy Policy*, **113**, 76–86. https://doi.org/10.1016/j.enpol.2017.10.057

30. Noblet, C.L., M.F. Teisl, K. Evans, M.W. Anderson, S. McCoy, and E. Cervone, 2015: Public preferences for investments in renewable energy production and energy efficiency. *Energy Policy*, **87**, 177–186. https://doi.org/10.1016/j.enpol.2015.09.003

31. Manley, D.K., V.A. Hines, M.W. Jordan, and R.E. Stoltz, 2013: A survey of energy policy priorities in the United States: Energy supply security, economics, and the environment. *Energy Policy*, **60**, 687–696. https://doi.org/10.1016/j.enpol.2013.04.061

32. Belussi, L., B. Barozzi, A. Bellazzi, L. Danza, A. Devitofrancesco, C. Fanciulli, M. Ghellere, G. Guazzi, I. Meroni, F. Salamone, F. Scamoni, and C. Scrosati, 2019: A review of performance of zero energy buildings and energy efficiency solutions. *Journal of Building Engineering*, **25**, 100772. https://doi.org/10.1016/j.jobe.2019.100772

33. Chen, S., G. Zhang, X. Xia, S. Setunge, and L. Shi, 2020: A review of internal and external influencing factors on energy efficiency design of buildings. *Energy and Buildings*, **216**, 109944. https://doi.org/10.1016/j.enbuild.2020.109944

34. Holz-Rau, C. and J. Scheiner, 2019: Land-use and transport planning – A field of complex cause-impact relationships. Thoughts on transport growth, greenhouse gas emissions and the built environment. *Transport Policy*, **74**, 127–137. https://doi.org/10.1016/j.tranpol.2018.12.004

35. Tayarani, M., A. Poorfakhraei, R. Nadafianshahamabadi, and G. Rowangould, 2018: Can regional transportation and land-use planning achieve deep reductions in GHG emissions from vehicles? *Transportation Research Part D: Transport and Environment*, **63**, 222–235. https://doi.org/10.1016/j.trd.2018.05.010

36. Neves, A. and C. Brand, 2019: Assessing the potential for carbon emissions savings from replacing short car trips with walking and cycling using a mixed GPS-travel diary approach. *Transportation Research Part A: Policy and Practice*, **123**, 130–146. https://doi.org/10.1016/j.tra.2018.08.022

37. Oeschger, G., P. Carroll, and B. Caulfield, 2020: Micromobility and public transport integration: The current state of knowledge. *Transportation Research Part D: Transport and Environment*, **89**, 102628. https://doi.org/10.1016/j.trd.2020.102628

38. Hannan, M.A., M.M. Hoque, A. Hussain, Y. Yusof, and P.J. Ker, 2018: State-of-the-art and energy management system of lithium-ion batteries in electric vehicle applications: Issues and recommendations. *IEEE Access*, **6**, 19362–19378. https://doi.org/10.1109/access.2018.2817655

39. Leach, F., G. Kalghatgi, R. Stone, and P. Miles, 2020: The scope for improving the efficiency and environmental impact of internal combustion engines. *Transportation Engineering*, **1**, 100005. https://doi.org/10.1016/j.treng.2020.100005

40. Li, Z., A. Khajepour, and J. Song, 2019: A comprehensive review of the key technologies for pure electric vehicles. *Energy*, **182**, 824–839. https://doi.org/10.1016/j.energy.2019.06.077

41. Browning, M., J. McFarland, J. Bistline, G. Boyd, M. Muratori, M. Binsted, C. Harris, T. Mai, G. Blanford, J. Edmonds, A.A. Fawcett, O. Kaplan, and J. Weyant, 2023: Net-zero $CO_2$ by 2050 scenarios for the United States in the Energy Modeling Forum 37 study. *Energy and Climate Change*, **4**, 100104. https://doi.org/10.1016/j.egycc.2023.100104

42. Huppmann, D., J. Bistline, J. DeAngelo, R. Jones, J. McFarland, J. Weyant, and S.J. Davis, 2023: NCA5 Scenario Explorer and Data hosted by IIASA. Mitigation Chapter of the Fifth National Climate Assessment and the International Institute for Applied Systems Analysis. Vienna, Austria.

43. Azevedo, I.M.L., 2014: Consumer end-use energy efficiency and rebound effects. *Annual Review of Environment and Resources*, **39** (1), 393–418. https://doi.org/10.1146/annurev-environ-021913-153558

44. Saunders, H.D., J. Roy, I.M.L. Azevedo, D. Chakravarty, S. Dasgupta, S. de la Rue du Can, A. Druckman, R. Fouquet, M. Grubb, B. Lin, R. Lowe, R. Madlener, D.M. McCoy, L. Mundaca, T. Oreszczyn, S. Sorrell, D. Stern, K. Tanaka, and T. Wei, 2021: Energy efficiency: What has research delivered in the last 40 years? *Annual Review of Environment and Resources*, **46** (1), 135–165. https://doi.org/10.1146/annurev-environ-012320-084937

45. Azevedo, I., C. Bataille, J. Bistline, L. Clarke, and S. Davis, 2021: Net-zero emissions energy systems: What we know and do not know. *Energy and Climate Change*, **2**, 100049. https://doi.org/10.1016/j.egycc.2021.100049

46. Clack, C.T.M., A. Choukulkar, B. Coté, and S.A. McKee, 2021: A Plan for Economy-Wide Decarbonization of the United States. Vibrant Clean Energy, Boulder, CO, 18 pp. https://www.vibrantcleanenergy.com/wp-content/uploads/2021/10/US-Econ-Decarb_CCSA.pdf

47. DeAngelo, J., I. Azevedo, J. Bistline, L. Clarke, G. Luderer, E. Byers, and S.J. Davis, 2021: Energy systems in scenarios at net-zero $CO_2$ emissions. *Nature Communications*, **12** (1), 6096. https://doi.org/10.1038/s41467-021-26356-y

48. Jenkins, J.D., Z. Zhou, R. Ponciroli, R.B. Vilim, F. Ganda, F. de Sisternes, and A. Botterud, 2018: The benefits of nuclear flexibility in power system operations with renewable energy. *Applied Energy*, **222**, 872–884. https://doi.org/10.1016/j.apenergy.2018.03.002

49. Larson, E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, E. Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan, 2021: Final Report Summary—Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Princeton University, Princeton, NJ. https://netzeroamerica.princeton.edu/the-report

50. Murray, B.C., J. Bistline, J. Creason, E. Wright, A. Kanudia, and F. de la Chesnaye, 2018: The EMF 32 study on technology and climate policy strategies for greenhouse gas reductions in the U.S. electric power sector: An overview. *Energy Economics*, **73**, 286–289. https://doi.org/10.1016/j.eneco.2018.03.007

51. Pacala, S.W., G.C. Hurtt, D. Baker, P. Peylin, R.A. Houghton, R.A. Birdsey, L. Heath, E.T. Sundquist, R.F. Stallard, P. Ciais, P. Moorcroft, J.P. Caspersen, E. Shevliakova, B. Moore, G. Kohlmaier, E. Holland, M. Gloor, M.E. Harmon, S.M. Fan, J.L. Sarmiento, C.L. Goodale, D. Schimel, and C.B. Field, 2001: Consistent land- and atmosphere-based U.S. carbon sink estimates. *Science*, **292** (5525), 2316–2320. https://doi.org/10.1126/science.1057320

52. Williams, J.H., R.A. Jones, B. Haley, G. Kwok, J. Hargreaves, J. Farbes, and M.S. Torn, 2021: Carbon-neutral pathways for the United States. AGU *Advances*, **2** (1), e2020AV000284. https://doi.org/10.1029/2020av000284

53. Bistline, J.E.T. and G.J. Blanford, 2021: The role of the power sector in net-zero energy systems. *Energy and Climate Change*, **2**, 100045. https://doi.org/10.1016/j.egycc.2021.100045

54. Inflation Reduction Act of 2022. 117th Congress, Pub. L. No. 117-169, 136 Stat. 1818, August 16, 2022. https://www.congress.gov/bill/117th-congress/house-bill/5376/text

55. Cole, W.J., D. Greer, P. Denholm, A.W. Frazier, S. Machen, T. Mai, N. Vincent, and S.F. Baldwin, 2021: Quantifying the challenge of reaching a 100% renewable energy power system for the United States. *Joule*, **5** (7), 1732–1748. https://doi.org/10.1016/j.joule.2021.05.011

56. Bistline, J.E.T. and G.J. Blanford, 2021: Impact of carbon dioxide removal technologies on deep decarbonization of the electric power sector. *Nature Communications*, **12** (1), 3732. https://doi.org/10.1038/s41467-021-23554-6

57. EPRI, 2022: Nuclear Energy in Long-Term System Models: A Multi-Model Perspective. Electric Power Research Institute, 136 pp. https://www.epri.com/research/products/000000003002023697

58. Bloom, A., L. Azar, J. Caspary, D. Lew, N. Miller, A. Silverstein, J. Simonelli, and R. Zavadil, 2021: Transmission Planning for 100% Clean Electricity. Energy Systems Integration Group, 29 pp. https://www.esig.energy/wp-content/uploads/2021/02/Transmission-Planning-White-Paper.pdf

59. Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.A. Frew, 2015: Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (49), 15060–15065. https://doi.org/10.1073/pnas.1510028112

60. Bistline, J.E.T., 2021: Roadmaps to net-zero emissions systems: Emerging insights and modeling challenges. *Joule*, **5** (10), 2551–2563. https://doi.org/10.1016/j.joule.2021.09.012

61. Mai, T.T., P. Jadun, J.S. Logan, C.A. McMillan, M. Muratori, D.C. Steinberg, L.J. Vimmerstedt, B. Haley, R. Jones, and B. Nelson, 2018: Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States. NREL/TP-6A20-71500. U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO. https://doi.org/10.2172/1459351

62. Ueckerdt, F., C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, and G. Luderer, 2021: Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nature Climate Change*, **11** (5), 384–393. https://doi.org/10.1038/s41558-021-01032-7

63. Hardman, S., 2019: Understanding the impact of reoccurring and non-financial incentives on plug-in electric vehicle adoption – A review. *Transportation Research Part A: Policy and Practice*, **119**, 1–14. https://doi.org/10.1016/j.tra.2018.11.002

64. Jenn, A., I.L. Azevedo, and P. Ferreira, 2013: The impact of federal incentives on the adoption of hybrid electric vehicles in the United States. *Energy Economics*, **40**, 936–942. https://doi.org/10.1016/j.eneco.2013.07.025

65. Jenn, A., K. Springel, and A.R. Gopal, 2018: Effectiveness of electric vehicle incentives in the United States. *Energy Policy*, **119**, 349–356. https://doi.org/10.1016/j.enpol.2018.04.065

66. Muratori, M., M. Alexander, D. Arent, M. Bazilian, P. Cazzola, E.M. Dede, J. Farrell, C. Gearhart, D. Greene, A. Jenn, M. Keyser, T. Lipman, S. Narumanchi, A. Pesaran, R. Sioshansi, E. Suomalainen, G. Tal, K. Walkowicz, and J. Ward, 2021: The rise of electric vehicles—2020 status and future expectations. *Progress in Energy*, **3** (2), 022002. https://doi.org/10.1088/2516-1083/abe0ad

67. Rietmann, N., B. Hügler, and T. Lieven, 2020: Forecasting the trajectory of electric vehicle sales and the consequences for worldwide $CO_2$ emissions. *Journal of Cleaner Production*, **261**, 121038. https://doi.org/10.1016/j.jclepro.2020.121038

68. Tong, F., A. Jenn, D. Wolfson, C.D. Scown, and M. Auffhammer, 2021: Health and climate impacts from long-haul truck electrification. *Environmental Science & Technology*, **55** (13), 8514–8523. https://doi.org/10.1021/acs.est.1c01273

69. Borlaug, B., M. Muratori, M. Gilleran, D. Woody, W. Muston, T. Canada, A. Ingram, H. Gresham, and C. McQueen, 2021: Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems. *Nature Energy*, **6** (6), 673–682. https://doi.org/10.1038/s41560-021-00855-0

70. Forrest, K., M. Mac Kinnon, B. Tarroja, and S. Samuelsen, 2020: Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. *Applied Energy*, **276**, 115439. https://doi.org/10.1016/j.apenergy.2020.115439

71. Phadke, A.A., A. Khandekar, N. Abhyankar, D. Wooley, and D. Rajagopal, 2021: Why Regional and Long-Haul Trucks are Primed for Electrification Now. U.S. Department of Energy, Lawrence Berkeley National Laboratory, Berkeley, CA. https://eta-publications.lbl.gov/publications/why-regional-and-long-haul-trucks-are

72. Smith, D., R. Graves, B. Ozpineci, P.T. Jones, J. Lustbader, K. Kelly, K. Walkowicz, A. Birky, G. Payne, C. Sigler, and J. Mosbacher, 2020: Medium- and Heavy-Duty Vehicle Electrification: An Assessment of Technology and Knowledge Gaps. ORNL/SPR-2020/7. U.S. Department of Energy, Oak Ridge National Laboratory and National Renewable Energy Laboratory. https://info.ornl.gov/sites/publications/files/pub136575.pdf

73. Tong, F., D. Wolfson, A. Jenn, C.D. Scown, and M. Auffhammer, 2021: Energy consumption and charging load profiles from long-haul truck electrification in the United States. *Environmental Research: Infrastructure and Sustainability*, **1** (2), 025007. https://doi.org/10.1088/2634-4505/ac186a

74. Bergero, C., G. Gosnell, D. Gielen, S. Kang, M. Bazilian, and S.J. Davis, 2023: Pathways to net-zero emissions from aviation. *Nature Sustainability*, **6** (4), 404–414. https://doi.org/10.1038/s41893-022-01046-9

75. Davis, S.J., N.S. Lewis, M. Shaner, S. Aggarwal, D. Arent, I.L. Azevedo, S.M. Benson, T. Bradley, J. Brouwer, Y.-M. Chiang, C.T.M. Clack, A. Cohen, S. Doig, J. Edmonds, P. Fennell, C.B. Field, B. Hannegan, B.-M. Hodge, M.I. Hoffert, E. Ingersoll, P. Jaramillo, K.S. Lackner, K.J. Mach, M. Mastrandrea, J. Ogden, P.F. Peterson, D.L. Sanchez, D. Sperling, J. Stagner, J.E. Trancik, C.-J. Yang, and K. Caldeira, 2018: Net-zero emissions energy systems. *Science*, **360** (6396), 9793. https://doi.org/10.1126/science.aas9793

76. Deason, J. and M. Borgeson, 2019: Electrification of buildings: Potential, challenges, and outlook. *Current Sustainable/Renewable Energy Reports*, **6** (4), 131–139. https://doi.org/10.1007/s40518-019-00143-2

77. Mahone, A., C. Li, Z. Subin, M. Sontag, G. Mantegna, A. Karolides, A.K.A. German, and P. Morris, 2019: Residential Building Electrification in California: Consumer Economics, Greenhouse Gases and Grid Impacts. Energy and Environmental Economics, San Francisco, CA. https://www.ethree.com/wp-content/uploads/2019/04/E3_Residential_Building_Electrification_in_California_April_2019.pdf

78. Tarroja, B., F. Chiang, A. AghaKouchak, S. Samuelsen, S.V. Raghavan, M. Wei, K. Sun, and T. Hong, 2018: Translating climate change and heating system electrification impacts on building energy use to future greenhouse gas emissions and electric grid capacity requirements in California. *Applied Energy*, **225**, 522–534. https://doi.org/10.1016/j.apenergy.2018.05.003

79. Madeddu, S., F. Ueckerdt, M. Pehl, J. Peterseim, M. Lord, K.A. Kumar, C. Krüger, and G. Luderer, 2020: The $CO_2$ reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environmental Research Letters*, **15** (12), 124004. https://doi.org/10.1088/1748-9326/abbd02

80. Bataille, C., M. Åhman, K. Neuhoff, L.J. Nilsson, M. Fischedick, S. Lechtenböhmer, B. Solano-Rodriquez, A. Denis-Ryan, S. Stiebert, H. Waisman, O. Sartor, and S. Rahbar, 2018: A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *Journal of Cleaner Production*, **187**, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107

81. Bataille, C.G.F., 2020: Physical and policy pathways to net-zero emissions industry. *WIREs Climate Change*, **11** (2), e633. https://doi.org/10.1002/wcc.633

82. Denis-Ryan, A., C. Bataille, and F. Jotzo, 2016: Managing carbon-intensive materials in a decarbonizing world without a global price on carbon. *Climate Policy*, **16** (sup1), S110–S128. https://doi.org/10.1080/14693062.2016.1176008

83. Rissman, J., C. Bataille, E. Masanet, N. Aden, W.R. Morrow, N. Zhou, N. Elliott, R. Dell, N. Heeren, B. Huckestein, J. Cresko, S.A. Miller, J. Roy, P. Fennell, B. Cremmins, T. Koch Blank, D. Hone, E.D. Williams, S. de la Rue du Can, B. Sisson, M. Williams, J. Katzenberger, D. Burtraw, G. Sethi, H. Ping, D. Danielson, H. Lu, T. Lorber, J. Dinkel, and J. Helseth, 2020: Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Applied Energy*, **266**, 114848. https://doi.org/10.1016/j.apenergy.2020.114848

84. Thiel, G.P. and A.K. Stark, 2021: To decarbonize industry, we must decarbonize heat. *Joule*, **5** (3), 531–550. https://doi.org/10.1016/j.joule.2020.12.007

85. Fennell, P., J. Driver, C. Bataille, and S.J. Davis, 2022: Cement and steel—Nine steps to net zero. *Nature*, **603**, 574–577. https://doi.org/10.1038/d41586-022-00758-4

86. Winkler, K., R. Fuchs, M. Rounsevell, and M. Herold, 2021: Global land use changes are four times greater than previously estimated. *Nature Communications*, **12** (1), 2501. https://doi.org/10.1038/s41467-021-22702-2

87. Searchinger, T.D., S. Wirsenius, T. Beringer, and P. Dumas, 2018: Assessing the efficiency of changes in land use for mitigating climate change. *Nature*, **564** (7735), 249–253. https://doi.org/10.1038/s41586-018-0757-z

88. Hong, C., H. Zhao, Y. Qin, J.A. Burney, J. Pongratz, K. Hartung, Y. Liu, F.C. Moore, R.B. Jackson, Q. Zhang, and S.J. Davis, 2022: Land-use emissions embodied in international trade. *Science*, **376** (6593), 597–603. https://doi.org/10.1126/science.abj1572

89. Mathews, J.A. and H. Tan, 2009: Biofuels and indirect land use change effects: The debate continues. *Biofuels, Bioproducts and Biorefining*, **3** (3), 305–317. https://doi.org/10.1002/bbb.147

90. Mosier, S., S.C. Córdova, and G.P. Robertson, 2021: Restoring soil fertility on degraded lands to meet food, fuel, and climate security needs via perennialization. *Frontiers in Sustainable Food Systems*, **5**, 706142. https://doi.org/10.3389/fsufs.2021.706142

91. EPA, 2021: From Farm to Kitchen: The Environmental Impacts of U.S. Food Waste. EPA 600-R21 171. U.S. Environmental Protection Agency, Office of Research and Development. https://www.epa.gov/land-research/farm-kitchen-environmental-impacts-us-food-waste

92. Gustavsson, J., C. Cederberg, U. Sonesson, R. van Otterdijk, and A. Meybeck, 2011: Global Food Losses and Food Waste—Extent, Causes and Prevention. Food and Agriculture Organization of the United Nations, Rome, Italy. https://www.fao.org/3/i2697e/i2697e.pdf

93. Godfray, H.C.J., P. Aveyard, T. Garnett, J.W. Hall, T.J. Key, J. Lorimer, R.T. Pierrehumbert, P. Scarborough, M. Springmann, and S.A. Jebb, 2018: Meat consumption, health, and the environment. *Science*, **361** (6399), 5324. https://doi.org/10.1126/science.aam5324

94. Poore, J. and T. Nemecek, 2018: Reducing food's environmental impacts through producers and consumers. *Science*, **360** (6392), 987–992. https://doi.org/10.1126/science.aaq0216

95. Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515** (7528), 518–522. https://doi.org/10.1038/nature13959

96. Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, F. DeClerck, A. Wood, M. Jonell, M. Clark, L.J. Gordon, J. Fanzo, C. Hawkes, R. Zurayk, J.A. Rivera, W. De Vries, L. Majele Sibanda, A. Afshin, A. Chaudhary, M. Herrero, R. Agustina, F. Branca, A. Lartey, S. Fan, B. Crona, E. Fox, V. Bignet, M. Troell, T. Lindahl, S. Singh, S.E. Cornell, K. Srinath Reddy, S. Narain, S. Nishtar, and C.J.L. Murray, 2019: Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, **393** (10170), 447–492. https://doi.org/10.1016/s0140-6736(18)31788-4

97. Hong, C., J.A. Burney, J. Pongratz, J.E.M.S. Nabel, N.D. Mueller, R.B. Jackson, and S.J. Davis, 2021: Global and regional drivers of land-use emissions in 1961–2017. *Nature*, **589** (7843), 554–561. https://doi.org/10.1038/s41586-020-03138-y

98. Clark, M.A., N.G.G. Domingo, K. Colgan, S.K. Thakrar, D. Tilman, J. Lynch, I.L. Azevedo, and J.D. Hill, 2020: Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science*, **370** (6517), 705–708. https://doi.org/10.1126/science.aba7357

99. Schmidinger, K. and E. Stehfest, 2012: Including $CO_2$ implications of land occupation in LCAs—Method and example for livestock products. *The International Journal of Life Cycle Assessment*, **17** (8), 962–972. https://doi.org/10.1007/s11367-012-0434-7

100. Springmann, M., L. Spajic, M.A. Clark, J. Poore, A. Herforth, P. Webb, M. Rayner, and P. Scarborough, 2020: The healthiness and sustainability of national and global food based dietary guidelines: Modelling study. *BMJ*, **370**, m2322. https://doi.org/10.1136/bmj.m2322

101. Falcon, W.P., R.L. Naylor, and N.D. Shankar, 2022: Rethinking global food demand for 2050. *Population and Development Review*, **48** (4), 921–957. https://doi.org/10.1111/padr.12508

102. Domingo, N.G.G., S. Balasubramanian, S.K. Thakrar, M.A. Clark, P.J. Adams, J.D. Marshall, N.Z. Muller, S.N. Pandis, S. Polasky, A.L. Robinson, C.W. Tessum, D. Tilman, P. Tschofen, and J.D. Hill, 2021: Air quality–related health damages of food. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (20), e2013637118. https://doi.org/10.1073/pnas.2013637118

103. Coleman-Jensen, A., M.P. Rabbitt, C.A. Gregory, and A. Singh, 2022: Household Food Security in the United States in 2021. ERR-309. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=104655

104. Khaleel, A.A., T.J. Sauer, and J.C. Tyndall, 2020: Changes in deep soil organic carbon and soil properties beneath tree windbreak plantings in the U.S. Great Plains. *Agroforestry Systems*, **94** (2), 565–581. https://doi.org/10.1007/s10457-019-00425-0

105. Osorio, R.J., C.J. Barden, and I.A. Ciampitti, 2019: GIS approach to estimate windbreak crop yield effects in Kansas–Nebraska. *Agroforestry Systems*, **93** (4), 1567–1576. https://doi.org/10.1007/s10457-018-0270-2

106. Schoeneberger, M., G. Bentrup, H. de Gooijer, R. Soolanayakanahally, T. Sauer, J. Brandle, X. Zhou, and D. Current, 2012: Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture. *Journal of Soil and Water Conservation*, **67** (5), 128A–136A. https://doi.org/10.2489/jswc.67.5.128a

107. Meurer, K.H.E., N.R. Haddaway, M.A. Bolinder, and T. Kätterer, 2018: Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach. *Earth-Science Reviews*, **177**, 613–622. https://doi.org/10.1016/j.earscirev.2017.12.015

108. Tamburini, G., R. Bommarco, T.C. Wanger, C. Kremen, M.G.A. Van der Heijden, M. Liebman, and S. Hallin, 2020: Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances*, **6** (45), 1715. https://doi.org/10.1126/sciadv.aba1715

109. Sela, S., H.M. van Es, B.N. Moebius-Clune, R. Marjerison, J. Melkonian, D. Moebius-Clune, R. Schindelbeck, and S. Gomes, 2016: Adapt-N outperforms grower-selected nitrogen rates in northeast and midwestern United States strip trials. *Agronomy Journal*, **108** (4), 1726–1734. https://doi.org/10.2134/agronj2015.0606

110. Venterea, R.T., J.A. Coulter, and M.S. Dolan, 2016: Evaluation of intensive "4R" strategies for decreasing nitrous oxide emissions and nitrogen surplus in rainfed corn. *Journal of Environmental Quality*, **45** (4), 1186–1195. https://doi.org/10.2134/jeq2016.01.0024

111. Ruser, R. and R. Schulz, 2015: The effect of nitrification inhibitors on the nitrous oxide ($N_2O$) release from agricultural soils—A review. *Journal of Plant Nutrition and Soil Science*, **178** (2), 171–188. https://doi.org/10.1002/jpln.201400251

112. Eagle, A.J., L.P. Olander, K.L. Locklier, J.B. Heffernan, and E.S. Bernhardt, 2017: Fertilizer management and environmental factors drive $N_2O$ and $NO_3$ losses in corn: A meta-analysis. *Soil Science Society of America Journal*, **81** (5), 1191–1202. https://doi.org/10.2136/sssaj2016.09.0281

113. Muller, J., D. De Rosa, J. Friedl, M. De Antoni Migliorati, D. Rowlings, P. Grace, and C. Scheer, 2023: Combining nitrification inhibitors with a reduced N rate maintains yield and reduces $N_2O$ emissions in sweet corn. *Nutrient Cycling in Agroecosystems*, **125** (2), 107–121. https://doi.org/10.1007/s10705-021-10185-y

114. Ocko, I.B., T. Sun, D. Shindell, M. Oppenheimer, A.N. Hristov, S.W. Pacala, D.L. Mauzerall, Y. Xu, and S.P. Hamburg, 2021: Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming. *Environmental Research Letters*, **16** (5), 054042. https://doi.org/10.1088/1748-9326/abf9c8

115. IPCC, 2021: Summary for policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–32. https://doi.org/10.1017/9781009157896.001

116. Ocko, I.B., V. Naik, and D. Paynter, 2018: Rapid and reliable assessment of methane impacts on climate. *Atmospheric Chemistry and Physics*, **18** (21), 15555–15568. https://doi.org/10.5194/acp-18-15555-2018

117. Aydin, G., I. Karakurt, and K. Aydiner, 2012: Analysis and mitigation opportunities of methane emissions from the energy sector. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **34** (11), 967–982. https://doi.org/10.1080/15567031003716725

118. Kang, M., S. Christian, M.A. Celia, D.L. Mauzerall, M. Bill, A.R. Miller, Y. Chen, M.E. Conrad, T.H. Darrah, and R.B. Jackson, 2016: Identification and characterization of high methane-emitting abandoned oil and gas wells. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (48), 13636–13641. https://doi.org/10.1073/pnas.1605913113

119. Lauvaux, T., C. Giron, M. Mazzolini, A. d'Aspremont, R. Duren, D. Cusworth, D. Shindell, and P. Ciais, 2022: Global assessment of oil and gas methane ultra-emitters. *Science*, **375** (6580), 557–561. https://doi.org/10.1126/science.abj4351

120. Omara, M., N. Zimmerman, M.R. Sullivan, X. Li, A. Ellis, R. Cesa, R. Subramanian, A.A. Presto, and A.L. Robinson, 2018: Methane emissions from natural gas production sites in the United States: Data synthesis and national estimate. *Environmental Science & Technology*, **52** (21), 12915–12925. https://doi.org/10.1021/acs.est.8b03535

121. Fargione, J.E., S. Bassett, T. Boucher, S.D. Bridgham, R.T. Conant, S.C. Cook-patton, P.W. Ellis, A. Falcucci, J.W. Fourqurean, T. Gopalakrishna, H. Gu, B. Henderson, M.D. Hurteau, K.D. Kroeger, T. Kroeger, T.J. Lark, S.M. Leavitt, G. Lomax, R.I. McDonald, J.P. Megonigal, D.A. Miteva, C.J. Richardson, J. Sanderman, D. Shoch, S.A. Spawn, J.W. Veldman, C.A. WIlliams, P.B. Woodbury, C. Zganjar, M. Baranski, R.A. Houghton, E. Landis, E. McGlynn, W.H. Schlesinger, J.V. Siikamakiariana, E. Sutton-Grierand, and B.W. Griscom, 2018: Natural climate solutions for the United States. *Science Advances*, **4** (11), 1869. https://doi.org/10.1126/sciadv.aat1869

122. APA, 2012: APA Policy Guide on Smart Growth. American Planning Association. https://www.planning.org/policy/guides/adopted/smartgrowth.htm

123. Broitman, D. and E. Koomen, 2015: Residential density change: Densification and urban expansion. *Computers, Environment and Urban Systems*, **54**, 32–46. https://doi.org/10.1016/j.compenvurbsys.2015.05.006

124. Butler, B.J., P.F. Catanzaro, J.L. Greene, J.H. Hewes, M.A. Kilgore, D.B. Kittredge, Z. Ma, and M.L. Tyrrell, 2012: Taxing family forest owners: Implications of federal and state policies in the United States. *Journal of Forestry*, **110** (7), 371–380. https://doi.org/10.5849/jof.11-097

125. Cathcart, J.F., J.D. Kline, M. Delaney, and M. Tilton, 2007: Carbon storage and Oregon's land-use planning program. *Journal of Forestry*, **105** (4), 167–172. https://doi.org/10.1093/jof/105.4.167

126. Harris, N.L., D.A. Gibbs, A. Baccini, R.A. Birdsey, S. de Bruin, M. Farina, L. Fatoyinbo, M.C. Hansen, M. Herold, R.A. Houghton, P.V. Potapov, D.R. Suarez, R.M. Roman-Cuesta, S.S. Saatchi, C.M. Slay, S.A. Turubanova, and A. Tyukavina, 2021: Global maps of twenty-first century forest carbon fluxes. *Nature Climate Change*, **11** (3), 234–240. https://doi.org/10.1038/s41558-020-00976-6

127. Lister, A.J., H. Andersen, T. Frescino, D. Gatziolis, S. Healey, L.S. Heath, G.C. Liknes, R. McRoberts, G.G. Moisen, M. Nelson, R. Riemann, K. Schleeweis, T.A. Schroeder, J. Westfall, and B.T. Wilson, 2020: Use of remote sensing data to improve the efficiency of national forest inventories: A case study from the United States National Forest Inventory. *Forests*, **11** (12). https://doi.org/10.3390/f11121364

128. Zheng, B., P. Ciais, F. Chevallier, H. Yang, J.G. Canadell, Y. Chen, I.R. van der Velde, I. Aben, E. Chuvieco, S.J. Davis, M. Deeter, C. Hong, Y. Kong, H. Li, H. Li, X. Lin, K. He, and Q. Zhang, 2023: Record-high $CO_2$ emissions from boreal fires in 2021. *Science*, **379** (6635), 912–917. https://doi.org/10.1126/science.ade0805

129. Smith, O., O. Cattell, E. Farcot, R.D. O'Dea, and K.I. Hopcraft, 2022: The effect of renewable energy incorporation on power grid stability and resilience. *Science Advances*, **8** (9), 6734. https://doi.org/10.1126/sciadv.abj6734

130. Clarke, L., Y.-M. Wei, A. De La Vega Navarro, A. Garg, A.N. Hahmann, S. Khennas, I.M.L. Azevedo, A. Löschel, A.K. Singh, L. Steg, G. Strbac, and K. Wada, 2022: Ch. 6. Energy systems. In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY. https://doi.org/10.1017/9781009157926.008

131. Dowling, J.A., K.Z. Rinaldi, T.H. Ruggles, S.J. Davis, M. Yuan, F. Tong, N.S. Lewis, and K. Caldeira, 2020: Role of long-duration energy storage in variable renewable electricity systems. *Joule*, **4** (9), 1907–1928. https://doi.org/10.1016/j.joule.2020.07.007

132. Jenkins, J.D. and N.A. Sepulveda, 2021: Long-duration energy storage: A blueprint for research and innovation. *Joule*, **5** (9), 2241–2246. https://doi.org/10.1016/j.joule.2021.08.002

133. Sepulveda, N.A., J.D. Jenkins, F.J. de Sisternes, and R.K. Lester, 2018: The role of firm low-carbon electricity resources in deep decarbonization of power generation. *Joule*, **2** (11), 2403–2420. https://doi.org/10.1016/j.joule.2018.08.006

134. Sepulveda, N.A., J.D. Jenkins, A. Edington, D.S. Mallapragada, and R.K. Lester, 2021: The design space for long-duration energy storage in decarbonized power systems. *Nature Energy*, **6** (5), 506–516. https://doi.org/10.1038/s41560-021-00796-8

135. Shan, R., J. Reagan, S. Castellanos, S. Kurtz, and N. Kittner, 2022: Evaluating emerging long-duration energy storage technologies. *Renewable and Sustainable Energy Reviews*, **159**, 112240. https://doi.org/10.1016/j.rser.2022.112240

136. Tong, F., M. Yuan, N.S. Lewis, S.J. Davis, and K. Caldeira, 2020: Effects of deep reductions in energy storage costs on highly reliable wind and solar electricity systems. *iScience*, **23** (9), 101484. https://doi.org/10.1016/j.isci.2020.101484

137. Jayadev, G., B.D. Leibowicz, and E. Kutanoglu, 2020: U.S. electricity infrastructure of the future: Generation and transmission pathways through 2050. *Applied Energy*, **260**, 114267. https://doi.org/10.1016/j.apenergy.2019.114267

138. Fennell, P.S., S.J. Davis, and A. Mohammed, 2021: Decarbonizing cement production. *Joule*, **5** (6), 1305–1311. https://doi.org/10.1016/j.joule.2021.04.011

139. Sutherland, B.R., 2020: Sustainably heating heavy industry. *Joule*, **4** (1), 14–16. https://doi.org/10.1016/j.joule.2019.12.020

140. Waite, M. and V. Modi, 2020: Electricity load implications of space heating decarbonization pathways. *Joule*, **4** (2), 376–394. https://doi.org/10.1016/j.joule.2019.11.011

141. Brown, T., D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, 2018: Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy*, **160**, 720–739. https://doi.org/10.1016/j.energy.2018.06.222

142. Griffiths, S., B.K. Sovacool, J. Kim, M. Bazilian, and J.M. Uratani, 2021: Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options. *Energy Research & Social Science*, **80**, 102208. https://doi.org/10.1016/j.erss.2021.102208

143. Gusain, D., M. Cvetković, R. Bentvelsen, and P. Palensky, 2020: Technical assessment of large scale PEM electrolyzers as flexibility service providers. In: *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)*. Delft, Netherlands, 17–19 June 2020. IEEE. https://doi.org/10.1109/isie45063.2020.9152462

144. Reissner, R., S. You, C. Bourasseau, P. Marcuello, V. Lacroix, G. Lavaille, D.A. Greenhalgh, L. Abadia, C. Imboden, and M. Bornstein, 2019: Unified and standardized qualifying tests of electrolysers for grid services. *3rd European Grid Service Markets Symposium*, Lucerne, Switzerland, 3–4 July 2019. https://elib.dlr.de/129857/2/g0502-paper.pdf

145. Ruggles, T.H., J.A. Dowling, N.S. Lewis, and K. Caldeira, 2021: Opportunities for flexible electricity loads such as hydrogen production from curtailed generation. *Advances in Applied Energy*, **3**, 100051. https://doi.org/10.1016/j.adapen.2021.100051

146. Demirbas, A. and G. Arin, 2002: An overview of biomass pyrolysis. *Energy Sources*, **24** (5), 471–482. https://doi.org/10.1080/00908310252889979

147. Dincer, I. and C. Acar, 2015: Review and evaluation of hydrogen production methods for better sustainability. *International Journal of Hydrogen Energy*, **40** (34), 11094–11111. https://doi.org/10.1016/j.ijhydene.2014.12.035

148. Antonini, C., K. Treyer, A. Streb, M. van der Spek, C. Bauer, and M. Mazzotti, 2020: Hydrogen production from natural gas and biomethane with carbon capture and storage–A techno-environmental analysis. *Sustainable Energy & Fuels*, **4** (6), 2967–2986. https://doi.org/10.1039/d0se00222d

149. Howarth, R.W. and M.Z. Jacobson, 2021: How green is blue hydrogen? *Energy Science & Engineering*, **9** (10), 1676–1687. https://doi.org/10.1002/ese3.956

150. IEA, 2021: Global Hydrogen Review 2021. International Energy Agency. https://www.iea.org/reports/global-hydrogen-review-2021

151. Chiesa, P., G. Lozza, and L. Mazzocchi, 2005: Using hydrogen as gas turbine fuel. *Journal of Engineering for Gas Turbines and Power*, **127** (1), 73–80. https://doi.org/10.1115/1.1787513

152. Leicher, J., T. Nowakowski, A. Giese, and K. Görner, 2017: Power-to-gas and the consequences: Impact of higher hydrogen concentrations in natural gas on industrial combustion processes. *Energy Procedia*, **120**, 96–103. https://doi.org/10.1016/j.egypro.2017.07.157

153. DOE, 2021: Hydrogen Shot. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/eere/fuelcells/hydrogen-shot

154. IEA, 2019: The Future of Hydrogen: Seizing Today's Opportunities. International Energy Agency. https://www.iea.org/reports/the-future-of-hydrogen

155. Pasman, H.J. and W.J. Rogers, 2010: Safety challenges in view of the upcoming hydrogen economy: An overview. *Journal of Loss Prevention in the Process Industries*, **23** (6), 697–704. https://doi.org/10.1016/j.jlp.2010.06.002

156. Stępień, Z., 2021: A comprehensive overview of hydrogen-fueled internal combustion engines: Achievements and future challenges. *Energies*, **14** (20). https://doi.org/10.3390/en14206504

157. York, W.D., W.S. Ziminsky, and E. Yilmaz, 2013: Development and testing of a low $NO_x$ hydrogen combustion system for heavy duty gas turbines. *Proceedings of the ASME Turbo Expo 2012: Turbine Technical Conference and Exposition. Volume 2: Combustion, Fuels and Emissions, Parts A and B*, Copenhagen, Denmark, 11–15 June 2012. ASME, 1395–1405. https://doi.org/10.1115/gt2012-69913

158. Ocko, I.B. and S.P. Hamburg, 2022: Climate consequences of hydrogen emissions. *Atmospheric Chemistry and Physics*, **22** (14), 9349–9368. https://doi.org/10.5194/acp-22-9349-2022

159. Prather, M.J., 2003: An environmental experiment with $H_2$? *Science*, **302** (5645), 581–582. https://doi.org/10.1126/science.1091060

160. Nguyen, T.T., J.S. Park, W.S. Kim, S.H. Nahm, and U.B. Beak, 2020: Environment hydrogen embrittlement of pipeline steel X70 under various gas mixture conditions with in situ small punch tests. *Materials Science and Engineering: A*, **781**, 139114. https://doi.org/10.1016/j.msea.2020.139114

161. Sun, M., X. Huang, Y. Hu, and S. Lyu, 2022: Effects on the performance of domestic gas appliances operated on natural gas mixed with hydrogen. *Energy*, **244**, 122557. https://doi.org/10.1016/j.energy.2021.122557

162. Wu, X., H. Zhang, M. Yang, W. Jia, Y. Qiu, and L. Lan, 2022: From the perspective of new technology of blending hydrogen into natural gas pipelines transmission: Mechanism, experimental study, and suggestions for further work of hydrogen embrittlement in high-strength pipeline steels. *International Journal of Hydrogen Energy*, **47** (12), 8071–8090. https://doi.org/10.1016/j.ijhydene.2021.12.108

163. Zhao, Y., V. McDonell, and S. Samuelsen, 2019: Experimental assessment of the combustion performance of an oven burner operated on pipeline natural gas mixed with hydrogen. *International Journal of Hydrogen Energy*, **44** (47), 26049–26062. https://doi.org/10.1016/j.ijhydene.2019.08.011

164. Zhao, Y., V. McDonell, and S. Samuelsen, 2019: Influence of hydrogen addition to pipeline natural gas on the combustion performance of a cooktop burner. *International Journal of Hydrogen Energy*, **44** (23), 12239–12253. https://doi.org/10.1016/j.ijhydene.2019.03.100

165. Haley, B., R.A. Jones, J.H. Williams, G. Kwok, J. Farbes, J. Hargreaves, K. Pickrell, D. Bentz, A. Waddell, and E. Leslie, 2022: Annual Decarbonization Perspective: Carbon-Neutral Pathways for the United States 2022. Evolved Energy Research. https://www.evolved.energy/post/adp2022

166. Caldeira, K., G. Bala, and L. Cao, 2013: The science of geoengineering. *Annual Review of Earth and Planetary Sciences*, **41** (1), 231–256. https://doi.org/10.1146/annurev-earth-042711-105548

167. National Academies of Sciences, Engineering, and Medicine, 2019: *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. The National Academies Press, Washington, DC, 510 pp. https://doi.org/10.17226/25259

168. Smith, P., S.J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R.B. Jackson, A. Cowie, E. Kriegler, D.P. van Vuuren, J. Rogelj, P. Ciais, J. Milne, J.G. Canadell, D. McCollum, G. Peters, R. Andrew, V. Krey, G. Shrestha, P. Friedlingstein, T. Gasser, A. Grubler, W.K. Heidug, M. Jonas, C.D. Jones, F. Kraxner, E. Littleton, J. Lowe, J.R. Moreira, N. Nakicenovic, M. Obersteiner, A. Patwardhan, M. Rogner, E. Rubin, A. Sharifi, A. Torvanger, Y. Yamagata, J. Edmonds, and C. Yongsung, 2016: Biophysical and economic limits to negative $CO_2$ emissions. *Nature Climate Change*, **6**, 42–50. https://doi.org/10.1038/nclimate2870

169. Batres, M., F.M. Wang, H. Buck, R. Kapila, U. Kosar, R. Licker, D. Nagabhushan, E. Rekhelman, and V. Suarez, 2021: Environmental and climate justice and technological carbon removal. *The Electricity Journal*, **34** (7), 107002. https://doi.org/10.1016/j.tej.2021.107002

170. Lee, K., C. Fyson, and C.-F. Schleussner, 2021: Fair distributions of carbon dioxide removal obligations and implications for effective national net-zero targets. *Environmental Research Letters*, **16** (9), 094001. https://doi.org/10.1088/1748-9326/ac1970

171. Fuhrman, J., C. Bergero, M. Weber, S. Monteith, F.M. Wang, A.F. Clarens, S.C. Doney, W. Shobe, and H. McJeon, 2023: Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nature Climate Change*, **13** (4), 341–350. https://doi.org/10.1038/s41558-023-01604-9

172. Chiquier, S., P. Patrizio, M. Bui, N. Sunny, and N. Mac Dowell, 2022: A comparative analysis of the efficiency, timing, and permanence of $CO_2$ removal pathways. *Energy and Environmental Science*, **15** (10), 4389–4403. https://doi.org/10.1039/d2ee01021f

173. Fankhauser, S., S.M. Smith, M. Allen, K. Axelsson, T. Hale, C. Hepburn, J.M. Kendall, R. Khosla, J. Lezaun, E. Mitchell-Larson, M. Obersteiner, L. Rajamani, R. Rickaby, N. Seddon, and T. Wetzer, 2022: The meaning of net zero and how to get it right. *Nature Climate Change*, **12** (1), 15–21. https://doi.org/10.1038/s41558-021-01245-w

174. Novick, K.A., S. Metzger, W.R.L. Anderegg, M. Barnes, D.S. Cala, K. Guan, K.S. Hemes, D.Y. Hollinger, J. Kumar, M. Litvak, D. Lombardozzi, C.P. Normile, P. Oikawa, B.R.K. Runkle, M. Torn, and S. Wiesner, 2022: Informing nature-based climate solutions for the United States with the best-available science. *Global Change Biology*, **28** (12), 3778–3794. https://doi.org/10.1111/gcb.16156

175. Sedjo, R. and B. Sohngen, 2012: Carbon sequestration in forests and soils. *Annual Review of Resource Economics*, **4** (1), 127–144. https://doi.org/10.1146/annurev-resource-083110-115941

176. McQueen, N., K.V. Gomes, C. McCormick, K. Blumanthal, M. Pisciotta, and J. Wilcox, 2021: A review of direct air capture (DAC): Scaling up commercial technologies and innovating for the future. *Progress in Energy*, **3** (3), 032001. https://doi.org/10.1088/2516-1083/abf1ce

177. Griscom, B.W., J. Adams, P.W. Ellis, R.A. Houghton, G. Lomax, D.A. Miteva, W.H. Schlesinger, D. Shoch, J.V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R.T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M.R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S.M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F.E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, and J. Fargione, 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

178. Cook-Patton, S.C., T. Gopalakrishna, A. Daigneault, S.M. Leavitt, J. Platt, S.M. Scull, O. Amarjargal, P.W. Ellis, B.W. Griscom, J.L. McGuire, S.M. Yeo, and J.E. Fargione, 2020: Lower cost and more feasible options to restore forest cover in the contiguous United States for climate mitigation. *One Earth*, **3** (6), 739–752. https://doi.org/10.1016/j.oneear.2020.11.013

179. Van Winkle, C., J. Baker, D. Lapidus, S.B. Ohrel, J. Steller, G. Latta, and D. Birur, 2017: Us Forest Sector Greenhouse Mitigation Potential and Implications for Nationally Determined Contributions. RTI Press Publication No. OP-0033-1705. RTI Press, Research Triangle Park, NC. https://doi.org/10.3768/rtipress.2017.op.0033.1705

180. Fargione, J., D.L. Haase, O.T. Burney, O.A. Kildisheva, G. Edge, S.C. Cook-Patton, T. Chapman, A. Rempel, M.D. Hurteau, K.T. Davis, S. Dobrowski, S. Enebak, R. De La Torre, A.A.R. Bhuta, F. Cubbage, B. Kittler, D. Zhang, and R.W. Guldin, 2021: Challenges to the reforestation pipeline in the United States. *Frontiers in Forests and Global Change*, **4**, 629198. https://doi.org/10.3389/ffgc.2021.629198

181. Bigelow, D.P. and A. Borchers, 2017: Major Uses of Land in the United States, 2012. EIB-178. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=84879

182. Conant, R.T., C.E.P. Cerri, B.B. Osborne, and K. Paustian, 2017: Grassland management impacts on soil carbon stocks: A new synthesis. *Ecological Applications*, **27** (2), 662–668. https://doi.org/10.1002/eap.1473

183. McSherry, M.E. and M.E. Ritchie, 2013: Effects of grazing on grassland soil carbon: A global review. *Global Change Biology*, **19** (5), 1347–1357. https://doi.org/10.1111/gcb.12144

184. Sanderson, J.S., C. Beutler, J.R. Brown, I. Burke, T. Chapman, R.T. Conant, J.D. Derner, M. Easter, S.D. Fuhlendorf, G. Grissom, J.E. Herrick, D. Liptzin, J.A. Morgan, R. Murph, C. Pague, I. Rangwala, D. Ray, R. Rondeau, T. Schulz, and T. Sullivan, 2020: Cattle, conservation, and carbon in the western Great Plains. *Journal of Soil and Water Conservation*, **75** (1), 5A–12A. https://doi.org/10.2489/jswc.75.1.5a

185. Bossio, D.A., S.C. Cook-Patton, P.W. Ellis, J. Fargione, J. Sanderman, P. Smith, S. Wood, R.J. Zomer, M. Unger, I.M. Emmer, and B.W. Griscom, 2020: The role of soil carbon in natural climate solutions. *Nature Sustainability*, **3**, 391–398. https://doi.org/10.1038/s41893-020-0491-z

186. Cai, A., T. Han, T. Ren, J. Sanderman, Y. Rui, B. Wang, P. Smith, M. Xu, and Y.e. Li, 2022: Declines in soil carbon storage under no tillage can be alleviated in the long run. *Geoderma*, **425**, 116028. https://doi.org/10.1016/j.geoderma.2022.116028

187. Lessmann, M., G.H. Ros, M.D. Young, and W. de Vries, 2022: Global variation in soil carbon sequestration potential through improved cropland management. *Global Change Biology*, **28** (3), 1162–1177. https://doi.org/10.1111/gcb.15954

188. Poeplau, C. and A. Don, 2015: Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment*, **200**, 33–41. https://doi.org/10.1016/j.agee.2014.10.024

189. D'Amato, A.W., J.B. Bradford, S. Fraver, and B.J. Palik, 2011: Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. *Forest Ecology and Management*, **262** (5), 803–816. https://doi.org/10.1016/j.foreco.2011.05.014

190. Jackson, R.B. and J.S. Baker, 2010: Opportunities and constraints for forest climate mitigation. *BioScience*, **60** (9), 698–707. https://doi.org/10.1525/bio.2010.60.9.7

191. Kaarakka, L., M. Cornett, G. Domke, T. Ontl, and L.E. Dee, 2021: Improved forest management as a natural climate solution: A review. *Ecological Solutions and Evidence*, **2** (3), e12090. https://doi.org/10.1002/2688-8319.12090

192. Lee, T.D., S.E. Eisenhaure, and I.P. Gaudreau, 2017: Pre-logging treatment of invasive glossy buckthorn (*Frangula alnus* mill.) promotes regeneration of eastern white pine (*Pinus strobus* L.). *Forests*, **8** (1), 16. https://doi.org/10.3390/f8010016

193. Moss, S.A. and E. Heitzman, 2013: The economic impact of timber harvesting practices on NIPF properties in West Virginia. In: *Proceedings, 18th Central Hardwood Forest Conference*, Miller, G.W., T.M. Schuler, K.W. Gottschalk, J.R. Brooks, S.T. Grushecky, B.D. Spong, and J.S. Rentch, Eds. Morgantown, WV, 26–28 March 2012. U.S. Department of Agriculture, Forest Service, Northern Research Station, 129–141. https://www.fs.usda.gov/research/treesearch/44060

194. Ontl, T.A., M.K. Janowiak, C.W. Swanston, J. Daley, S. Handler, M. Cornett, S. Hagenbuch, C. Handrick, L. McCarthy, and N. Patch, 2020: Forest management for carbon sequestration and climate adaptation. *Journal of Forestry*, **118** (1), 86–101. https://doi.org/10.1093/jofore/fvz062

195. Powers, M.D., R.K. Kolka, J.B. Bradford, B.J. Palik, S. Fraver, and M.F. Jurgensen, 2012: Carbon stocks across a chronosequence of thinned and unmanaged red pine (*Pinus resinosa*) stands. *Ecological Applications*, **22** (4), 1297–1307. https://doi.org/10.1890/11-0411.1

196. Schuler, T.M., M. Thomas-Van Gundy, J.P. Brown, and J.K. Wiedenbeck, 2017: Managing Appalachian hardwood stands using four management practices: 60-year results. *Forest Ecology and Management*, **387**, 3–11. https://doi.org/10.1016/j.foreco.2016.08.019

197. Byrd, K., J. Ratliff, N. Bliss, A. Wein, B. Sleeter, T. Sohl, and Z. Li, 2015: Quantifying climate change mitigation potential in the United States Great Plains wetlands for three greenhouse gas emission scenarios. *Mitigation and Adaptation Strategies for Global Change*, **20** (3), 439–465. https://doi.org/10.1007/s11027-013-9500-0

198. Byrd, K.B., L. Ballanti, N. Thomas, D. Nguyen, J.R. Holmquist, M. Simard, and L. Windham-Myers, 2018: A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States. *ISPRS Journal of Photogrammetry and Remote Sensing*, **139**, 255–271. https://doi.org/10.1016/j.isprsjprs.2018.03.019

199. Kroeger, K.D., S. Crooks, S. Moseman-Valtierra, and J. Tang, 2017: Restoring tides to reduce methane emissions in impounded wetlands: A new and potent Blue Carbon climate change intervention. *Scientific Reports*, **7** (1), 11914. https://doi.org/10.1038/s41598-017-12138-4

200. National Academies of Sciences, Engineering, and Medicine, 2022: *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*. The National Academies Press, Washington, DC, 322 pp. https://doi.org/10.17226/26278

201. Lampitt, R.S., E.P. Achterberg, T.R. Anderson, J.A. Hughes, M.D. Iglesias-Rodriguez, B.A. Kelly-Gerreyn, M. Lucas, E.E. Popova, R. Sanders, J.G. Shepherd, D. Smythe-Wright, and A. Yool, 2008: Ocean fertilization: A potential means of geoengineering? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **366** (1882), 3919–3945. https://doi.org/10.1098/rsta.2008.0139

202. DeAngelo, J., B.T. Saenz, I.B. Arzeno-Soltero, C.A. Frieder, M.C. Long, J. Hamman, K.A. Davis, and S.J. Davis, 2023: Economic and biophysical limits to seaweed farming for climate change mitigation. *Nature Plants*, **9** (1), 45–57. https://doi.org/10.1038/s41477-022-01305-9

203. Bach, L.T., S.J. Gill, R.E.M. Rickaby, S. Gore, and P. Renforth, 2019: $CO_2$ removal with enhanced weathering and ocean alkalinity enhancement: Potential risks and co-benefits for marine pelagic ecosystems. *Frontiers in Climate*, **1**, 7. https://doi.org/10.3389/fclim.2019.00007

204. Drouet, L., V. Bosetti, S.A. Padoan, L. Aleluia Reis, C. Bertram, F. Dalla Longa, J. Després, J. Emmerling, F. Fosse, K. Fragkiadakis, S. Frank, O. Fricko, S. Fujimori, M. Harmsen, V. Krey, K. Oshiro, L.P. Nogueira, L. Paroussos, F. Piontek, K. Riahi, P.R.R. Rochedo, R. Schaeffer, J.y. Takakura, K.-I. van der Wijst, B. van der Zwaan, D. van Vuuren, Z. Vrontisi, M. Weitzel, B. Zakeri, and M. Tavoni, 2021: Net zero-emission pathways reduce the physical and economic risks of climate change. *Nature Climate Change*, **11** (12), 1070–1076. https://doi.org/10.1038/s41558-021-01218-z

205. Jones, C.D., P. Ciais, S.J. Davis, P. Friedlingstein, T. Gasser, G.P. Peters, J. Rogelj, D.P. van Vuuren, J.G. Canadell, A. Cowie, R.B. Jackson, M. Jonas, E. Kriegler, E. Littleton, J.A. Lowe, J. Milne, G. Shrestha, P. Smith, A. Torvanger, and A. Wiltshire, 2016: Simulating the Earth system response to negative emissions. *Environmental Research Letters*, **11** (9), 095012. https://doi.org/10.1088/1748-9326/11/9/095012

206. Koven, C.D., B.M. Sanderson, and A.L.S. Swann, 2023: Much of zero emissions commitment occurs before reaching net zero emissions. *Environmental Research Letters*, **18** (1), 014017. https://doi.org/10.1088/1748-9326/acab1a

207. National Academies of Sciences, Engineering, and Medicine, 2021: *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*. The National Academies Press, Washington, DC, 328 pp. https://doi.org/10.17226/25762

208. OSTP, 2023: Congressionally-mandated report on solar radiation modification. White House Office of Science and Technology Policy, Washington, DC, June 30, 2023. https://www.whitehouse.gov/ostp/news-updates/2023/06/30/congressionally-mandated-report-on-solar-radiation-modification/

209. Fagnant, D.J. and K. Kockelman, 2015: Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, **77**, 167–181. https://doi.org/10.1016/j.tra.2015.04.003

210. Motamedi, S., P. Wang, T. Zhang, and C.-Y. Chan, 2020: Acceptance of full driving automation: Personally owned and shared-use concepts. *Human Factors*, **62** (2), 288–309. https://doi.org/10.1177/0018720819870658

211. Brown, K.E. and R. Dodder, 2019: Energy and emissions implications of automated vehicles in the U.S. energy system. *Transportation Research Part D: Transport and Environment*, **77**, 132–147. https://doi.org/10.1016/j.trd.2019.09.003

212. Massar, M., I. Reza, S.M. Rahman, S.M.H. Abdullah, A. Jamal, and F.S. Al-Ismail, 2021: Impacts of autonomous vehicles on greenhouse gas emissions—Positive or negative? *International Journal of Environmental Research and Public Health*, **18** (11), 5567. https://doi.org/10.3390/ijerph18115567

213. Sheppard, C.J.R., A.T. Jenn, J.B. Greenblatt, G.S. Bauer, and B.F. Gerke, 2021: Private versus shared, automated electric vehicles for U.S. personal mobility: Energy use, greenhouse gas emissions, grid integration, and cost impacts. *Environmental Science and Technology*, **55** (5), 3229–3239. https://doi.org/10.1021/acs.est.0c06655

214. Abduljabbar, R.L., S. Liyanage, and H. Dia, 2021: The role of micro-mobility in shaping sustainable cities: A systematic literature review. *Transportation Research Part D: Transport and Environment*, **92**, 102734. https://doi.org/10.1016/j.trd.2021.102734

215. Hidaka, K. and T. Shiga, 2018: Forecasting travel demand for new mobility services employing autonomous vehicles. *Transportation Research Procedia*, **34**, 139–146. https://doi.org/10.1016/j.trpro.2018.11.025

216. Kamargianni, M., W. Li, M. Matyas, and A. Schäfer, 2016: A critical review of new mobility services for urban transport. *Transportation Research Procedia*, **14**, 3294–3303. https://doi.org/10.1016/j.trpro.2016.05.277

217. Fleming, K.L., 2018: Social equity considerations in the new age of transportation: Electric, automated, and shared mobility. *Journal of Science Policy & Governance*, **13** (1). https://www.sciencepolicyjournal.org/uploads/5/4/3/4/5434385/fleming.pdf

218. Jenn, A., 2020: Emissions benefits of electric vehicles in Uber and Lyft ride-hailing services. *Nature Energy*, **5** (7), 520–525. https://doi.org/10.1038/s41560-020-0632-7

219. Taiebat, M. and M. Xu, 2019: Synergies of four emerging technologies for accelerated adoption of electric vehicles: Shared mobility, wireless charging, vehicle-to-grid, and vehicle automation. *Journal of Cleaner Production*, **230**, 794–797. https://doi.org/10.1016/j.jclepro.2019.05.142

220. Arent, D.J., C. Barrows, S. Davis, G. Grim, J. Schaidle, B. Kroposki, M. Ruth, and B. Van Zandt, 2022: Integration of energy systems. *MRS Bulletin*, **46** (12), 1139–1152. https://doi.org/10.1557/s43577-021-00244-8

221. Ramsebner, J., R. Haas, A. Ajanovic, and M. Wietschel, 2021: The sector coupling concept: A critical review. *WIREs Energy and Environment*, **10** (4), e396. https://doi.org/10.1002/wene.396

222. Rodríguez Escobar, M.I., E. Cadena, T.T. Nhu, M. Cooreman-Algoed, S. De Smet, and J. Dewulf, 2021: Analysis of the cultured meat production system in function of its environmental footprint: Current status, gaps and recommendations. *Foods*, **10** (12), 2941. https://doi.org/10.3390/foods10122941

223. Rubio, N.R., N. Xiang, and D.L. Kaplan, 2020: Plant-based and cell-based approaches to meat production. *Nature Communications*, **11** (1), 6276. https://doi.org/10.1038/s41467-020-20061-y

224. Tubb, C. and T. Seba, 2021: Rethinking food and agriculture 2020-2030: The second domestication of plants and animals, the disruption of the cow, and the collapse of industrial livestock farming. *Industrial Biotechnology*, **17** (2), 57–72. https://doi.org/10.1089/ind.2021.29240.ctu

225. García Martínez, J.B., K.A. Alvarado, and D.C. Denkenberger, 2022: Synthetic fat from petroleum as a resilient food for global catastrophes: Preliminary techno-economic assessment and technology roadmap. *Chemical Engineering Research and Design*, **177**, 255–272. https://doi.org/10.1016/j.cherd.2021.10.017

226. MacDougall, A.H., J. Rogelj, and P. Withey, 2021: Estimated climate impact of replacing agriculture as the primary food production system. *Environmental Research Letters*, **16** (12), 125010. https://doi.org/10.1088/1748-9326/ac3aa5

227. Almeida, A.K., R.S. Hegarty, and A. Cowie, 2021: Meta-analysis quantifying the potential of dietary additives and rumen modifiers for methane mitigation in ruminant production systems. *Animal Nutrition*, **7** (4), 1219–1230. https://doi.org/10.1016/j.aninu.2021.09.005

228. Roque, B.M., M. Venegas, R.D. Kinley, R. de Nys, T.L. Duarte, X. Yang, and E. Kebreab, 2021: Red seaweed (*Asparagopsis taxiformis*) supplementation reduces enteric methane by over 80 percent in beef steers. *PLoS ONE*, **16** (3), e0247820. https://doi.org/10.1371/journal.pone.0247820

229. Pape, D., J. Lewandrowski, R. Steele, D. Man, M. Riley-Gilbert, K. Moffroid, and S. Kolansky, 2016: Managing Agricultural Land for Greenhouse Gas Mitigation Within the United States. ICF International. https://www.usda.gov/sites/default/files/documents/White_Paper_WEB71816.pdf

230. Souza, R., J. Yin, and S. Calabrese, 2021: Optimal drainage timing for mitigating methane emissions from rice paddy fields. *Geoderma*, **394**, 114986. https://doi.org/10.1016/j.geoderma.2021.114986

231. Subbarao, G.V. and T.D. Searchinger, 2021: A "more ammonium solution" to mitigate nitrogen pollution and boost crop yields. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (22), e2107576118. https://doi.org/10.1073/pnas.2107576118

232. Lelieveld, J., K. Klingmüller, A. Pozzer, R.T. Burnett, A. Haines, and V. Ramanathan, 2019: Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (15), 7192–7197. https://doi.org/10.1073/pnas.1819989116

233. Shindell, D., M. Ru, Y. Zhang, K. Seltzer, G. Faluvegi, L. Nazarenko, G.A. Schmidt, L. Parsons, A. Challapalli, L. Yang, and A. Glick, 2021: Temporal and spatial distribution of health, labor, and crop benefits of climate change mitigation in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (46), e2104061118. https://doi.org/10.1073/pnas.2104061118

234. Tessum, C.W., J.S. Apte, A.L. Goodkind, N.Z. Muller, K.A. Mullins, D.A. Paolella, S. Polasky, N.P. Springer, S.K. Thakrar, J.D. Marshall, and J.D. Hill, 2019: Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6001–6006. https://doi.org/10.1073/pnas.1818859116

235. Tessum, C.W., J.D. Hill, and J.D. Marshall, 2017: InMAP: A model for air pollution interventions. *PLoS ONE*, **12** (4), e0176131. https://doi.org/10.1371/journal.pone.0176131

236. Thakrar, S.K., S. Balasubramanian, P.J. Adams, I.M.L. Azevedo, N.Z. Muller, S.N. Pandis, S. Polasky, C.A. Pope, A.L. Robinson, J.S. Apte, C.W. Tessum, J.D. Marshall, and J.D. Hill, 2020: Reducing mortality from air pollution in the United States by targeting specific emission sources. *Environmental Science & Technology Letters*, **7** (9), 639–645. https://doi.org/10.1021/acs.estlett.0c00424

237. Vohra, K., A. Vodonos, J. Schwartz, E.A. Marais, M.P. Sulprizio, and L.J. Mickley, 2021: Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. *Environmental Research*, **195**, 110754. https://doi.org/10.1016/j.envres.2021.110754

238. Murray, C.J.L., A.Y. Aravkin, P. Zheng, C. Abbafati, K.M. Abbas, et al., 2020: Global burden of 87 risk factors in 204 countries and territories, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, **396** (10258), 1223–1249. https://doi.org/10.1016/s0140-6736(20)30752-2

239. Brook, R.D., S. Rajagopalan, C.A. Pope, J.R. Brook, A. Bhatnagar, A.V. Diez-Roux, F. Holguin, Y. Hong, R.V. Luepker, M.A. Mittleman, A. Peters, D. Siscovick, S.C. Smith, L. Whitsel, and J.D. Kaufman, 2010: Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circulation*, **121** (21), 2331–2378. https://doi.org/10.1161/cir.0b013e3181dbece1

240. Crouse, D.L., P.A. Peters, A. van Donkelaar, M.S. Goldberg, P.J. Villeneuve, O. Brion, S. Khan, D.O. Atari, M. Jerrett, C.A. Pope, M. Brauer, J.R. Brook, R.V. Martin, D. Stieb, and R.T. Burnett, 2012: Risk of nonaccidental and cardiovascular mortality in relation to long-term exposure to low concentrations of fine particulate matter: A Canadian national-level cohort study. *Environmental Health Perspectives*, **120** (5), 708–714. https://doi.org/10.1289/ehp.1104049

241. Pope, C.A. and D.W. Dockery, 2006: Health effects of fine particulate air pollution: Lines that connect. *Journal of the Air & Waste Management Association*, **56** (6), 709–742. https://doi.org/10.1080/10473289.2006.10464485

242. Hajat, A., C. Hsia, and M.S. O'Neill, 2015: Socioeconomic disparities and air pollution exposure: A global review. *Current Environmental Health Reports*, **2** (4), 440–450. https://doi.org/10.1007/s40572-015-0069-5

243. Liu, J., L.P. Clark, M.J. Bechle, A. Hajat, S.Y. Kim, A.L. Robinson, L. Sheppard, A.A. Szpiro, and J.D. Marshall, 2021: Disparities in air pollution exposure in the United States by race/ethnicity and income, 1990–2010. *Environmental Health Perspectives*, **129** (12), 127005. https://doi.org/10.1289/ehp8584

244. Mikati, I., A.F. Benson, T.J. Luben, J.D. Sacks, and J. Richmond-Bryant, 2018: Disparities in distribution of particulate matter emission sources by race and poverty status. *American Journal of Public Health*, **108** (4), 480–485. https://doi.org/10.2105/ajph.2017.304297

245. Tessum, C.W., D.A. Paolella, S.E. Chambliss, J.S. Apte, J.D. Hill, and J.D. Marshall, 2021: $PM_{2.5}$ polluters disproportionately and systemically affect people of color in the United States. *Science Advances*, **7** (18), 4491. https://doi.org/10.1126/sciadv.abf4491

246. Thind, M.P.S., C.W. Tessum, I.L. Azevedo, and J.D. Marshall, 2019: Fine particulate air pollution from electricity generation in the US: Health impacts by race, income, and geography. *Environmental Science & Technology*, **53** (23), 14010–14019. https://doi.org/10.1021/acs.est.9b02527

247. Mayfield, E.N., J.L. Cohon, N.Z. Muller, I.M.L. Azevedo, and A.L. Robinson, 2019: Quantifying the social equity state of an energy system: Environmental and labor market equity of the shale gas boom in Appalachia. *Environmental Research Letters*, **14** (12), 124072. https://doi.org/10.1088/1748-9326/ab59cd

248. Markandya, A., J. Sampedro, S.J. Smith, R. Van Dingenen, C. Pizarro-Irizar, I. Arto, and M. González-Eguino, 2018: Health co-benefits from air pollution and mitigation costs of the Paris Agreement: A modelling study. *The Lancet Planetary Health*, **2** (3), e126–e133. https://doi.org/10.1016/s2542-5196(18)30029-9

249. Vandyck, T., K. Keramidas, A. Kitous, J.V. Spadaro, R. Van Dingenen, M. Holland, and B. Saveyn, 2018: Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nature Communications*, **9** (1), 4939. https://doi.org/10.1038/s41467-018-06885-9

250. Zhang, Y., S.J. Smith, J.H. Bowden, Z. Adelman, and J.J. West, 2017: Co-benefits of global, domestic, and sectoral greenhouse gas mitigation for US air quality and human health in 2050. *Environmental Research Letters*, **12** (11), 114033. https://doi.org/10.1088/1748-9326/aa8f76

251. Zhu, S., M. Mac Kinnon, A. Carlos-Carlos, S.J. Davis, and S. Samuelsen, 2022: Decarbonization will lead to more equitable air quality in California. *Nature Communications*, **13** (1), 5738. https://doi.org/10.1038/s41467-022-33295-9

252. Gallagher, C.L. and T. Holloway, 2020: Integrating air quality and public health benefits in U.S. decarbonization strategies. *Frontiers in Public Health*, **8**, 563358. https://doi.org/10.3389/fpubh.2020.563358

253. Mayfield, E.N., 2022: Phasing out coal power plants based on cumulative air pollution impact and equity objectives in net zero energy system transitions. *Environmental Research: Infrastructure and Sustainability*, **2** (2), 021004. https://doi.org/10.1088/2634-4505/ac70f6

254. Sergi, B.J., P.J. Adams, N.Z. Muller, A.L. Robinson, S.J. Davis, J.D. Marshall, and I.L. Azevedo, 2020: Optimizing emissions reductions from the U.S. power sector for climate and health benefits. *Environmental Science & Technology*, **54** (12), 7513–7523. https://doi.org/10.1021/acs.est.9b06936

255. Barbose, G., R. Wiser, J. Heeter, T. Mai, L. Bird, M. Bolinger, A. Carpenter, G. Heath, D. Keyser, J. Macknick, A. Mills, and D. Millstein, 2016: A retrospective analysis of benefits and impacts of U.S. renewable portfolio standards. *Energy Policy*, **96**, 645–660. https://doi.org/10.1016/j.enpol.2016.06.035

256. Buonocore, J.J., P. Luckow, G. Norris, J.D. Spengler, B. Biewald, J. Fisher, and J.I. Levy, 2016: Health and climate benefits of different energy-efficiency and renewable energy choices. *Nature Climate Change*, **6** (1), 100–105. https://doi.org/10.1038/nclimate2771

257. Dimanchev, E.G., S. Paltsev, M. Yuan, D. Rothenberg, C.W. Tessum, J.D. Marshall, and N.E. Selin, 2019: Health co-benefits of sub-national renewable energy policy in the US. *Environmental Research Letters*, **14** (8), 085012. https://doi.org/10.1088/1748-9326/ab31d9

258. Millstein, D., R. Wiser, M. Bolinger, and G. Barbose, 2017: The climate and air-quality benefits of wind and solar power in the United States. *Nature Energy*, **2** (9), 17134. https://doi.org/10.1038/nenergy.2017.134

259. Qiu, M., C.M. Zigler, and N.E. Selin, 2022: Impacts of wind power on air quality, premature mortality, and exposure disparities in the United States. *Science Advances*, **8** (48), 8762. https://doi.org/10.1126/sciadv.abn8762

260. Siler-Evans, K., I.L. Azevedo, M.G. Morgan, and J. Apt, 2013: Regional variations in the health, environmental, and climate benefits of wind and solar generation. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (29), 11768–11773. https://doi.org/10.1073/pnas.1221978110

261. Grabow, M.L., S.N. Spak, T. Holloway, B. Stone, Jr. , A.C. Mednick, and J.A. Patz, 2012: Air quality and exercise-related health benefits from reduced car travel in the midwestern United States. *Environmental Health Perspectives*, **120** (1), 68–76. https://doi.org/10.1289/ehp.1103440

262. Tong, F. and I.M.L. Azevedo, 2020: What are the best combinations of fuel-vehicle technologies to mitigate climate change and air pollution effects across the United States? *Environmental Research Letters*, **15** (7), 074046. https://doi.org/10.1088/1748-9326/ab8a85

263. Deetjen, T.A., L. Walsh, and P. Vaishnav, 2021: US residential heat pumps: The private economic potential and its emissions, health, and grid impacts. *Environmental Research Letters*, **16** (8), 084024. https://doi.org/10.1088/1748-9326/ac10dc

264. Commane, R. and L.D. Schiferl, 2022: Climate mitigation policies for cities must consider air quality impacts. *Chem*, **8** (4), 910–923. https://doi.org/10.1016/j.chempr.2022.02.006

265. Gross, S., 2020: Renewables, Land Use, and Local Opposition in the United States. The Brookings Institution, 24 pp. https://www.brookings.edu/research/renewables-land-use-and-local-opposition-in-the-united-states/

266. Mulvaney, D., 2017: Identifying the roots of Green Civil War over utility-scale solar energy projects on public lands across the American Southwest. *Journal of Land Use Science*, **12** (6), 493–515. https://doi.org/10.1080/1747423x.2017.1379566

267. Nielsen, J.A.E., K. Stavrianakis, and Z. Morrison, 2022: Community acceptance and social impacts of carbon capture, utilization and storage projects: A systematic meta-narrative literature review. *PLoS ONE*, **17** (8), e0272409. https://doi.org/10.1371/journal.pone.0272409

268. Cox, E., E. Spence, and N. Pidgeon, 2020: Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nature Climate Change*, **10** (8), 744–749. https://doi.org/10.1038/s41558-020-0823-z

269. Hernandez, R.R., S.B. Easter, M.L. Murphy-Mariscal, F.T. Maestre, M. Tavassoli, E.B. Allen, C.W. Barrows, J. Belnap, R. Ochoa-Hueso, S. Ravi, and M.F. Allen, 2014: Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews*, **29**, 766–779. https://doi.org/10.1016/j.rser.2013.08.041

270. Hernandez, R.R., M.K. Hoffacker, M.L. Murphy-Mariscal, G.C. Wu, and M.F. Allen, 2015: Solar energy development impacts on land cover change and protected areas. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (44), 13579–13584. https://doi.org/10.1073/pnas.1517656112

271. Laranjeiro, T., R. May, and F. Verones, 2018: Impacts of onshore wind energy production on birds and bats: Recommendations for future life cycle impact assessment developments. *The International Journal of Life Cycle Assessment*, **23** (10), 2007–2023. https://doi.org/10.1007/s11367-017-1434-4

272. Hall, P.K., W. Morgan, and J. Richardson, 2022: Land Use Conflicts Between Wind and Solar Renewable Energy and Agricultural Uses. The National Agricultural Law Center. https://researchrepository.wvu.edu/cgi/viewcontent.cgi?article=1104&context=law_faculty

273. Hill, J., 2022: The sobering truth about corn ethanol. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (11), e2200997119. https://doi.org/10.1073/pnas.2200997119

274. Lark, T.J., N.P. Hendricks, A. Smith, N. Pates, S.A. Spawn-Lee, M. Bougie, E.G. Booth, C.J. Kucharik, and H.K. Gibbs, 2022: Environmental outcomes of the US renewable fuel standard. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (9), e2101084119. https://doi.org/10.1073/pnas.2101084119

275. Wu, G.C., E. Leslie, O. Sawyerr, D.R. Cameron, E. Brand, B. Cohen, D. Allen, M. Ochoa, and A. Olson, 2020: Low-impact land use pathways to deep decarbonization of electricity. *Environmental Research Letters*, **15** (7), 074044. https://doi.org/10.1088/1748-9326/ab87d1

276. Gerrard, M.B. and E. McTiernan, 2020: New York's new statute on siting renewable energy facilities. *New York Law Journal*, **263** (93). https://scholarship.law.columbia.edu/faculty_scholarship/3026

277. Moch, J.M. and H. Lee, 2022: The Challenges of Decarbonizing the U.S. Electric Grid by 2035. Harvard University, Harvard Kennedy School, Belfer Center, Cambridge, MA. https://www.belfercenter.org/publication/challenges-decarbonizing-us-electric-grid-2035

278. Susskind, L., J. Chun, A. Gant, C. Hodgkins, J. Cohen, and S. Lohmar, 2022: Sources of opposition to renewable energy projects in the United States. *Energy Policy*, **165**, 112922. https://doi.org/10.1016/j.enpol.2022.112922

279. Grubert, E. and A. Marshall, 2022: Water for energy: Characterizing co-evolving energy and water systems under twin climate and energy system nonstationarities. *WIREs Water*, **9** (2), e1576. https://doi.org/10.1002/wat2.1576

280. Grubert, E. and K.T. Sanders, 2018: Water use in the United States energy system: A national assessment and unit process inventory of water consumption and withdrawals. *Environmental Science & Technology*, **52** (11), 6695–6703. https://doi.org/10.1021/acs.est.8b00139

281. Peer, R.A.M., E. Grubert, and K.T. Sanders, 2019: A regional assessment of the water embedded in the US electricity system. *Environmental Research Letters*, **14** (8), 084014. https://doi.org/10.1088/1748-9326/ab2daa

282. Qin, Y., N.D. Mueller, S. Siebert, R.B. Jackson, A. AghaKouchak, J.B. Zimmerman, D. Tong, C. Hong, and S.J. Davis, 2019: Flexibility and intensity of global water use. *Nature Sustainability*, **2** (6), 515–523. https://doi.org/10.1038/s41893-019-0294-2

283. Tarroja, B., R.A.M. Peer, K.T. Sanders, and E. Grubert, 2020: How do non-carbon priorities affect zero-carbon electricity systems? A case study of freshwater consumption and cost for Senate Bill 100 compliance in California. *Applied Energy*, **265**, 114824. https://doi.org/10.1016/j.apenergy.2020.114824

284. Grubert, E., 2023: Water consumption from electrolytic hydrogen in a carbon-neutral US energy system. *Cleaner Production Letters*, **4**, 100037. https://doi.org/10.1016/j.clpl.2023.100037

285. Lampert, D.J., H. Cai, and A. Elgowainy, 2016: Wells to wheels: Water consumption for transportation fuels in the United States. *Energy & Environmental Science*, **9** (3), 787–802. https://doi.org/10.1039/c5ee03254g

286. Rosa, L., D.L. Sanchez, G. Realmonte, D. Baldocchi, and P. D'Odorico, 2021: The water footprint of carbon capture and storage technologies. *Renewable and Sustainable Energy Reviews*, **138**, 110511. https://doi.org/10.1016/j.rser.2020.110511

287. Lovering, J., M. Swain, L. Blomqvist, and R.R. Hernandez, 2022: Land-use intensity of electricity production and tomorrow's energy landscape. *PLoS ONE*, **17** (7), e0270155. https://doi.org/10.1371/journal.pone.0270155

288. BLS, 2022: Local Area Unemployment Statistics. U.S. Bureau of Labor Statistics. https://www.bls.gov/lau/home.htm

289. DOE, 2022: United States Energy and Employment Report 2022. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2022-06/USEER%202022%20National%20Report_1.pdf

290. DOL, n.d.: Prevailing Wage and the Inflation Reduction Act. U.S. Department of Labor, accessed May 9, 2023. https://www.dol.gov/agencies/whd/ira

291. NASEO and EFI, 2020: The 2019 U.S. Energy & Employment Report. National Association of State Energy Officials and Energy Futures Initiative. https://www.naseo.org/data/sites/1/documents/publications/useer-2019-us-energy-employment-report1.pdf

292. Mayfield, E.N., J.L. Cohon, N.Z. Muller, I.M.L. Azevedo, and A.L. Robinson, 2019: Cumulative environmental and employment impacts of the shale gas boom. *Nature Sustainability*, **2** (12), 1122–1131. https://doi.org/10.1038/s41893-019-0420-1

293. Mayfield, E., J. Jenkins, E. Larson, and C. Greig, 2021: Labor Pathways to Achieve Net-Zero Emissions in the United States by Mid-Century. USAEE Working Paper No. 21-494. U.S. Association for Energy Economics, 83 pp. https://doi.org/10.2139/ssrn.3834083

294. Bergquist, P., M. Mildenberger, and L.C. Stokes, 2020: Combining climate, economic, and social policy builds public support for climate action in the US. *Environmental Research Letters*, **15** (5), 054019. https://doi.org/10.1088/1748-9326/ab81c1

295. Blyth, W., J. Speirs, and R. Gross, 2014: Low carbon jobs: The evidence for net job creation from policy support for energy efficiency and renewable energy. In: *BIEE 10th Academic Conference*. 17–18 September 2014. U.K. Energy Research Centre, 31 pp. https://www.biee.org/wpcms/wp-content/uploads/Speirs-Low-carbon-jobs-The-evidence-for-net-job-creation.pdf

296. Pollin, R. and S. Chakraborty, 2020: Job Creation Estimates Through Proposed Economic Stimulus Measures. University of Massachusetts, Political Economy Research Institute, Amherst, MA. https://peri.umass.edu/publication/item/1297-job-creation-estimates-through-proposed-economic-stimulus-measures

297. Wei, M., S. Patadia, and D.M. Kammen, 2010: Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, **38** (2), 919–931. https://doi.org/10.1016/j.enpol.2009.10.044

298. Mayfield, E. and J. Jenkins, 2021: Influence of high road labor policies and practices on renewable energy costs, decarbonization pathways, and labor outcomes. *Environmental Research Letters*, **16** (12), 124012. https://doi.org/10.1088/1748-9326/ac34ba

299. Bergquist, P., S. Ansolabehere, S. Carley, and D. Konisky, 2020: Backyard voices: How sense of place shapes views of large-scale energy transmission infrastructure. *Energy Research & Social Science*, **63**, 101396. https://doi.org/10.1016/j.erss.2019.101396

300. Chapman, A.J., B.C. McLellan, and T. Tezuka, 2018: Prioritizing mitigation efforts considering co-benefits, equity and energy justice: Fossil fuel to renewable energy transition pathways. *Applied Energy*, **219**, 187–198. https://doi.org/10.1016/j.apenergy.2018.03.054

301. Henry, M.S., M.D. Bazilian, and C. Markuson, 2020: Just transitions: Histories and futures in a post-COVID world. *Energy Research & Social Science*, **68**, 101668. https://doi.org/10.1016/j.erss.2020.101668

302. Cha, J.M., 2020: A just transition for whom? Politics, contestation, and social identity in the disruption of coal in the Powder River Basin. *Energy Research and Social Science*, **69**, 101657. https://doi.org/10.1016/j.erss.2020.101657

303. Pai, S., H. Zerriffi, J. Jewell, and J. Pathak, 2020: Solar has greater techno-economic resource suitability than wind for replacing coal mining jobs. *Environmental Research Letters*, **15** (3), 034065. https://doi.org/10.1088/1748-9326/ab6c6d

304. Carley, S., T.P. Evans, and D.M. Konisky, 2018: Adaptation, culture, and the energy transition in American coal country. *Energy Research & Social Science*, **37**, 133–139. https://doi.org/10.1016/j.erss.2017.10.007

305. Pollin, R. and B. Callaci, 2019: The economics of just transition: A framework for supporting fossil fuel-dependent workers and communities in the United States. *Labor Studies Journal*, **44** (2), 93–138. https://doi.org/10.1177/0160449x18787051

306. CRS, 2022: Proposed Tax Preference for Domestic Content in Energy Infrastructure. CRS Report IN11983. Congressional Research Service. https://crsreports.congress.gov/product/pdf/in/in11983

307. NETL, 2022: Energy Community Tax Credit Bonus. U.S. Department of Energy, National Energy Technology Laboratory. https://energycommunities.gov/energy-community-tax-credit-bonus/

308. Jenkins, J.D., E.N. Mayfield, E.D. Larson, S.W. Pacala, and C. Greig, 2021: Mission net-zero America: The nation-building path to a prosperous, net-zero emissions economy. *Joule*, **5** (11), 2755–2761. https://doi.org/10.1016/j.joule.2021.10.016

309. Carley, S. and D.M. Konisky, 2020: The justice and equity implications of the clean energy transition. *Nature Energy*, **5** (8), 569–577. https://doi.org/10.1038/s41560-020-0641-6

310. Jenkins, K., D. McCauley, R. Heffron, H. Stephan, and R. Rehner, 2016: Energy justice: A conceptual review. *Energy Research & Social Science*, **11**, 174–182. https://doi.org/10.1016/j.erss.2015.10.004

311. Banzhaf, S., L. Ma, and C. Timmins, 2019: Environmental justice: The economics of race, place, and pollution. *Journal of Economic Perspectives*, **33** (1), 185–208. https://doi.org/10.1257/jep.33.1.185

312. Fefferman, N., C.-F. Chen, G. Bonilla, H. Nelson, and C.-P. Kuo, 2021: How limitations in energy access, poverty, and socioeconomic disparities compromise health interventions for outbreaks in urban settings. *iScience*, **24** (12), 103389. https://doi.org/10.1016/j.isci.2021.103389

313. Hernández, D., 2016: Understanding 'energy insecurity' and why it matters to health. *Social Science & Medicine*, **167**, 1–10. https://doi.org/10.1016/j.socscimed.2016.08.029

314. Lane, H.M., R. Morello-Frosch, J.D. Marshall, and J.S. Apte, 2022: Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environmental Science & Technology Letters*, **9** (4), 345–350. https://doi.org/10.1021/acs.estlett.1c01012

315. Brown, M., A. Soni, M. Lapsa, and K. Southworth, 2020: Low-Income Energy Affordability: Conclusions from a Literature Review. ORNL/TM-2019/1150. U.S. Department of Energy, Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/files/pub124723.pdf

316. Drehobl, A. and L. Ross, 2016: Lifting the High Energy Burden in America's Largest Cities: How Energy Efficiency Can Improve Low Income and Underserved Communities. American Council for an Energy Efficient Economy. https://www.aceee.org/sites/default/files/publications/researchreports/u1602.pdf

317. Drehobl, A., L. Ross, and R. Ayala, 2020: How High Are Household Energy Burdens? An Assessment of National and Metropolitan Energy Burden across the United States. American Council for an Energy-Efficient Economy, Washington, DC. https://www.aceee.org/sites/default/files/pdfs/u2006.pdf

318. Lewis, J., D. Hernández, and A.T. Geronimus, 2020: Energy efficiency as energy justice: Addressing racial inequities through investments in people and places. *Energy Efficiency*, **13** (3), 419–432. https://doi.org/10.1007/s12053-019-09820-z

319. Reames, T.G., 2016: A community-based approach to low-income residential energy efficiency participation barriers. *Local Environment*, **21** (12), 1449–1466. https://doi.org/10.1080/13549839.2015.1136995

320. Ross, L., A. Drehobl, and B. Stickles, 2018: The High Cost of Energy in Rural America: Household Energy Burdens and Opportunities for Energy Efficiency. American Council for an Energy-Efficient Economy, Washington DC. https://www.aceee.org/sites/default/files/publications/researchreports/u1806.pdf

321. Bednar, D.J. and T.G. Reames, 2020: Recognition of and response to energy poverty in the United States. *Nature Energy*, **5** (6), 432–439. https://doi.org/10.1038/s41560-020-0582-0

322. Benz, S.A. and J.A. Burney, 2021: Widespread race and class disparities in surface urban heat extremes across the United States. *Earth's Future*, **9** (7), e2021EF002016. https://doi.org/10.1029/2021ef002016

323. Benz, S.A., S.J. Davis, and J.A. Burney, 2021: Drivers and projections of global surface temperature anomalies at the local scale. *Environmental Research Letters*, **16** (6), 064093. https://doi.org/10.1088/1748-9326/ac0661

324. McDonald, R.I., T. Biswas, C. Sachar, I. Housman, T.M. Boucher, D. Balk, D. Nowak, E. Spotswood, C.K. Stanley, and S. Leyk, 2021: The tree cover and temperature disparity in US urbanized areas: Quantifying the association with income across 5,723 communities. *PLoS ONE*, **16** (4), e0249715. https://doi.org/10.1371/journal.pone.0249715

325. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. https://doi.org/10.3390/cli8010012

326. Plumer, B. and N. Popovich, 2020: How decades of racist housing policy left neighborhoods sweltering. *The New York Times*, August 24, 2020. https://www.nytimes.com/interactive/2020/08/24/climate/racism-redlining-cities-global-warming.html

327. Chen, M., G.A. Ban-Weiss, and K.T. Sanders, 2020: Utilizing smart-meter data to project impacts of urban warming on residential electricity use for vulnerable populations in Southern California. *Environmental Research Letters*, **15** (6), 064001. https://doi.org/10.1088/1748-9326/ab6fbe

328. Sherwin, E.D. and I.M.L. Azevedo, 2020: Characterizing the association between low-income electric subsidies and the intra-day timing of electricity consumption. *Environmental Research Letters*, **15** (9), 094089. https://doi.org/10.1088/1748-9326/aba030

329. Cong, S., D. Nock, Y.L. Qiu, and B. Xing, 2022: Unveiling hidden energy poverty using the energy equity gap. *Nature Communications*, **13** (1), 2456. https://doi.org/10.1038/s41467-022-30146-5

330. Scheier, E. and N. Kittner, 2022: A measurement strategy to address disparities across household energy burdens. *Nature Communications*, **13** (1), 288. https://doi.org/10.1038/s41467-021-27673-y

331. Gillingham, K., R.G. Newell, and K. Palmer, 2009: Energy efficiency economics and policy. *Annual Review of Resource Economics*, **1** (1), 597–620. https://doi.org/10.1146/annurev.resource.102308.124234

332. Baniassadi, A., D.J. Sailor, E.S. Krayenhoff, A.M. Broadbent, and M. Georgescu, 2019: Passive survivability of buildings under changing urban climates across eight US cities. *Environmental Research Letters*, **14** (7), 074028. https://doi.org/10.1088/1748-9326/ab28ba

333. Sunter, D.A., S. Castellanos, and D.M. Kammen, 2019: Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity. *Nature Sustainability*, **2** (1), 71–76. https://doi.org/10.1038/s41893-018-0204-z

334. Welton, S. and J.B. Eisen, 2019: Clean energy justice: Charting an emerging agenda. *Harvard Environmental Law Review*, **43**, 307–371. https://scholarship.law.upenn.edu/faculty_scholarship/2842

335. Carley, S., T.P. Evans, M. Graff, and D.M. Konisky, 2018: A framework for evaluating geographic disparities in energy transition vulnerability. *Nature Energy*, **3** (8), 621–627. https://doi.org/10.1038/s41560-018-0142-z

336. Jessel, S., S. Sawyer, and D. Hernández, 2019: Energy, poverty, and health in climate change: A comprehensive review of an emerging literature. *Frontiers in Public Health*, **7**, 357. https://doi.org/10.3389/fpubh.2019.00357

337. IEA, 2021: The Role of Critical Minerals in Clean Energy Transitions. International Energy Agency. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

338. Lee, J., M. Bazilian, and S. Hastings-Simon, 2021: The material foundations of a low-carbon economy. *One Earth*, **4** (3), 331–334. https://doi.org/10.1016/j.oneear.2021.02.015

339. Lee, J., M. Bazilian, B. Sovacool, K. Hund, S.M. Jowitt, T.P. Nguyen, A. Månberger, M. Kah, S. Greene, C. Galeazzi, K. Awuah-Offei, M. Moats, J. Tilton, and S. Kukoda, 2020: Reviewing the material and metal security of low-carbon energy transitions. *Renewable and Sustainable Energy Reviews*, **124**, 109789. https://doi.org/10.1016/j.rser.2020.109789

340. Sovacool, B.K., S.H. Ali, M. Bazilian, B. Radley, B. Nemery, J. Okatz, and D. Mulvaney, 2020: Sustainable minerals and metals for a low-carbon future. *Science*, **367** (6437), 30–33. https://doi.org/10.1126/science.aaz6003

341. Nassar, N.T. and S.M. Fortier, 2021: Methodology and Technical Input for the 2021 Review and Revision of the U.S. Critical Minerals List. USGS Open-File Report 2021–1045. U.S. Geological Survey, 31 pp. https://doi.org/10.3133/ofr20211045

342. U.S. Geological Survey, 2022: 2022 final list of critical minerals. *Federal Register*, **87** (37), 10381–10382. https://www.federalregister.gov/documents/2022/02/24/2022-04027/2022-final-list-of-critical-minerals

343. Executive Office of the President, 2017: Executive Order 13817: A federal strategy to ensure secure and reliable supplies of critical minerals. *Federal Register*, **82** (246), 60835–60837. https://www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals

344. Executive Office of the President, 2020: Executive Order 13953: Addressing the threat to the domestic supply chain from reliance on critical minerals from foreign adversaries and supporting the domestic mining and processing industries. *Federal Register*, **85** (193), 62539–62544. https://www.federalregister.gov/documents/2020/10/05/2020-22064/addressing-the-threat-to-the-domestic-supply-chain-from-reliance-on-critical-minerals-from-foreign

345. Executive Office of the President, 2021: Executive Order 14017: America's supply chains. *Federal Register*, **86** (38), 11849–11854. https://www.federalregister.gov/documents/2021/03/01/2021-04280/americas-supply-chains

346. Fortier, S.M., J.H. DeYoung Jr., E.S. Sangine, and E.K. Schnebele, 2015: Comparison of U.S. Net Import Reliance for Nonfuel Mineral Commodities—A 60-Year Retrospective (1954–1984–2014). Fact Sheet 2015–3082. U.S. Geological Survey, 4 pp. https://doi.org/10.3133/fs20153082

347. DOE, 2022: The Inflation Reduction Act Drives Significant Emissions Reductions and Positions America to Reach our Climate Goals. DOE/OP-0018. U.S. Department of Energy, Office of Policy, 6 pp. https://www.energy.gov/sites/default/files/2022-08/8.18%20InflationReductionAct_Factsheet_Final.pdf

348. C2ES, 2023: State Climate Policy Maps. Center for Climate and Energy Solutions. https://www.c2es.org/content/state-climate-policy/

349. UNFCCC, 2022: Actor Tracking. United Nations Framework Convention on Climate Change. https://climateaction.unfccc.int/actors

350. Peñasco, C., L.D. Anadón, and E. Verdolini, 2021: Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments. *Nature Climate Change*, **11** (3), 257–265. https://doi.org/10.1038/s41558-020-00971-x

351. Agriculture Resilience Act. H.R. 2803, 117th Congress, 2021. https://www.congress.gov/bill/117th-congress/house-bill/2803/text

352. SEC, 2022: SEC proposes rules to enhance and standardize climate-related disclosures for investors. U.S. Securities and Exchange Commission, Washington, DC, March 21, 2022. https://www.sec.gov/news/press-release/2022-46

353. Bjørn, A., S.M. Lloyd, M. Brander, and H.D. Matthews, 2022: Renewable energy certificates threaten the integrity of corporate science-based targets. *Nature Climate Change*, **12** (6), 539–546. https://doi.org/10.1038/s41558-022-01379-5

354. Curtis, Q., J. Fisch, and A.Z. Robertson, 2021: Do ESG funds deliver on their promises? *Michigan Law Review*, **120** (3). https://doi.org/10.36644/mlr.120.3.esg

355. GHG Protocol, 2022: Land Sector and Removals Guidance. Greenhouse Gas Protocol. https://ghgprotocol.org/land-sector-and-removals-guidance

356. Oldfield, E.E., A.J. Eagle, R.L. Rubin, J. Rudek, J. Sanderman, and D.R. Gordon, 2022: Crediting agricultural soil carbon sequestration. *Science*, **375** (6586), 1222–1225. https://doi.org/10.1126/science.abl7991

357. Amorim-Maia, A.T., I. Anguelovski, E. Chu, and J. Connolly, 2022: Intersectional climate justice: A conceptual pathway for bridging adaptation planning, transformative action, and social equity. *Urban Climate*, **41**, 101053. https://doi.org/10.1016/j.uclim.2021.101053

358. Simon, K., G. Diprose, and A.C. Thomas, 2020: Community-led initiatives for climate adaptation and mitigation. *Kōtuitui: New Zealand Journal of Social Sciences Online*, **15** (1), 93–105. https://doi.org/10.1080/1177083x.2019.1652659

359. Troxler, T.G., A.C. Clement, Y. Arditi-Rocha, G. Beesing, M. Bhat, J. Bolson, C. Cabán-Alemán, K. Castillo, O. Collins, M. Cruz, A. Dodd, S.D. Evans, A.L. Fleming, C. Genatios, J. Gilbert, A. Hernandez, C. Holder, M. Ilcheva, E. Kelly, and E. Wheaton, 2021: A system for resilience learning: Developing a community-driven, multi-sector research approach for greater preparedness and resilience to long-term climate stressors and extreme events in the Miami metropolitan region. *Journal of Extreme Events*, **08** (03), 2150019. https://doi.org/10.1142/s2345737621500196

360. Farbes, J., B. Haley, and R. Jones, 2021: Marginal Abatement Cost Curves for U.S. Net-Zero Energy Systems: A Systems Approach. Evolved Energy Research, 52 pp. https://www.evolved.energy/post/mac2-0

361. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–33. https://doi.org/10.1017/9781009325844.001

362. Visit Florida, 2022: Florida Visitor Estimates [Webpage]. https://www.visitflorida.org/resources/research/

363. Visit Orlando, 2019: Orlando announces record 75 million visitors, solidifies ranking as No. 1 U.S. travel destination. Visit Orlando, Orlando, FL, May 9, 2019. https://www.visitorlando.com/media/press-releases/post/orlando-announces-record-75-million-visitors-solidifies-ranking-as-no-1-u-s-travel-destination/

364. FDOT, 2022: Central Florida Autonomous Vehicle Proving Ground. Florida Department of Transportation. https://www.fdot.gov/traffic/teo-divisions.shtm/cav-ml-stamp/cv/maplocations/cf-av.shtm

365. Ponnaluri, R., F. Heery, and V.Y. Tillander, 2017: The Florida connected and automated vehicle initiative: A focus on deployment. *ITE Journal*, **87** (10). https://trid.trb.org/view/1484058

366. MetroPlan Orlando, 2020: MetroPlan Orlando CAV Readiness Study: Final Report. MetroPlan Orlando. https://metroplanorlando.gov/wp-content/uploads/MetroPlan-CAV-Readiness-7.1.20-Final.pdf

367. USDA, 2009: Let's Glean! United We Serve Toolkit. U.S. Department of Agriculture, 8 pp. https://www.usda.gov/sites/default/files/documents/usda_gleaning_toolkit.pdf

368. EIA, 1992: Housing Characteristics 1990. DOE/EIA-0314(90). U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/consumption/residential/index.php

369. EIA, 1997: Manufacturing Energy Consumption Survey 1994. U.S. Energy Information Administration. https://www.eia.gov/consumption/manufacturing/data/1994/index.php?view=data

370. EIA, 2021: 2018 Manufacturing Energy Consumption Survey. U.S. Energy Information Administration. https://www.eia.gov/consumption/manufacturing/data/2018/

371. EIA, 2022: State Energy Data System (SEDS). U.S. Energy Information Administration. https://www.eia.gov/state/seds/

372. The World Bank, 2021: World Development Indicators. World Bank Group.

373. The World Bank, 2022: World Development Indicators. World Bank Group.

374. IPCC, 2019: *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Calvo Buendia, E., K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, S. Ngarize, A. Osako, Y. Pyrozhenko, P. Shermanau, and S. Federici, Eds. Intergovernmental Panel on Climate Change, Switzerland. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

375. Matthews, H.D., N.P. Gillett, P.A. Stott, and K. Zickfeld, 2009: The proportionality of global warming to cumulative carbon emissions. *Nature*, **459** (7248), 829–832. https://doi.org/10.1038/nature08047

376. Lyon, C., E.E. Saupe, C.J. Smith, D.J. Hill, A.P. Beckerman, L.C. Stringer, R. Marchant, J. McKay, A. Burke, P. O'Higgins, A.M. Dunhill, B.J. Allen, J. Riel-Salvatore, and T. Aze, 2022: Climate change research and action must look beyond 2100. *Global Change Biology*, **28** (2), 349–361. https://doi.org/10.1111/gcb.15871

377. McGlynn, E., S. Li, M. F. Berger, M. Amend, and K. L. Harper, 2022: Addressing uncertainty and bias in land use, land use change, and forestry greenhouse gas inventories. *Climatic Change*, **170** (1), 5. https://doi.org/10.1007/s10584-021-03254-2

378. Nisbet, E.G., R.E. Fisher, D. Lowry, J.L. France, G. Allen, S. Bakkaloglu, T.J. Broderick, M. Cain, M. Coleman, J. Fernandez, G. Forster, P.T. Griffiths, C.P. Iverach, B.F.J. Kelly, M.R. Manning, P.B.R. Nisbet-Jones, J.A. Pyle, A. Townsend-Small, A. al-Shalaan, N. Warwick, and G. Zazzeri, 2020: Methane mitigation: Methods to reduce emissions, on the path to the Paris Agreement. *Reviews of Geophysics*, **58** (1), e2019RG000675. https://doi.org/10.1029/2019rg000675

379. Saunois, M., A.R. Stavert, B. Poulter, P. Bousquet, J.G. Canadell, R.B. Jackson, P.A. Raymond, E.J. Dlugokencky, S. Houweling, P.K. Patra, P. Ciais, V.K. Arora, D. Bastviken, P. Bergamaschi, D.R. Blake, G. Brailsford, L. Bruhwiler, K.M. Carlson, M. Carrol, S. Castaldi, N. Chandra, C. Crevoisier, P.M. Crill, K. Covey, C.L. Curry, G. Etiope, C. Frankenberg, N. Gedney, M.I. Hegglin, L. Höglund-Isaksson, G. Hugelius, M. Ishizawa, A. Ito, G. Janssens-Maenhout, K.M. Jensen, F. Joos, T. Kleinen, P.B. Krummel, R.L. Langenfelds, G.G. Laruelle, L. Liu, T. Machida, S. Maksyutov, K.C. McDonald, J. McNorton, P.A. Miller, J.R. Melton, I. Morino, J. Müller, F. Murguia-Flores, V. Naik, Y. Niwa, S. Noce, S. O'Doherty, R.J. Parker, C. Peng, S. Peng, G.P. Peters, C. Prigent, R. Prinn, M. Ramonet, P. Regnier, W.J. Riley, J.A. Rosentreter, A. Segers, I.J. Simpson, H. Shi, S.J. Smith, L.P. Steele, B.F. Thornton, H. Tian, Y. Tohjima, F.N. Tubiello, A. Tsuruta, N. Viovy, A. Voulgarakis, T.S. Weber, M. van Weele, G.R. van der Werf, R.F. Weiss, D. Worthy, D. Wunch, Y. Yin, Y. Yoshida, W. Zhang, Z. Zhang, Y. Zhao, B. Zheng, Q. Zhu, Q. Zhu, and Q. Zhuang, 2020: The global methane budget 2000–2017. *Earth System Science Data*, **12** (3), 1561–1623. https://doi.org/10.5194/essd-12-1561-2020

380. Liu, M.J., K.N. Izquierdo, and D.S. Prince, 2022: Intelligent monitoring of fugitive emissions—Comparison of continuous monitoring with intelligent analytics to other emissions monitoring technologies. *The APPEA Journal*, **62**, 56–65. https://doi.org/10.1071/aj21116

381. Norooz Oliaee, J., N.A. Sabourin, S.A. Festa-Bianchet, J.A. Gupta, M.R. Johnson, K.A. Thomson, G.J. Smallwood, and P. Lobo, 2022: Development of a sub-ppb resolution methane sensor using a GaSb-based DFB diode laser near 3270 nm for fugitive emission measurement. *ACS Sensors*, **7** (2), 564–572. https://doi.org/10.1021/acssensors.1c02444

382. Conrad, B.M., D.R. Tyner, and M.R. Johnson, 2023: Robust probabilities of detection and quantification uncertainty for aerial methane detection: Examples for three airborne technologies. *Remote Sensing of Environment*, **288**, 113499. https://doi.org/10.1016/j.rse.2023.113499

383. Hurtt, G.C., S.W. Pacala, P.R. Moorcroft, J. Caspersen, E. Shevliakova, R.A. Houghton, and B. Moore, 2002: Projecting the future of the U.S. carbon sink. *Proceedings of the National Academy of Sciences of the United States of America*, **99** (3), 1389–1394. https://doi.org/10.1073/pnas.012249999

384. Wu, C., S.R. Coffield, M.L. Goulden, J.T. Randerson, A.T. Trugman, and W.R.L. Anderegg, 2023: Uncertainty in US forest carbon storage potential due to climate risks. *Nature Geoscience*, **16** (5), 422–429. https://doi.org/10.1038/s41561-023-01166-7

385. Kang, J.-N., Y.-M. Wei, L.-C. Liu, R. Han, B.-Y. Yu, and J.-W. Wang, 2020: Energy systems for climate change mitigation: A systematic review. *Applied Energy*, **263**, 114602. https://doi.org/10.1016/j.apenergy.2020.114602

386. Bataille, C., H. Waisman, M. Colombier, L. Segafredo, and J. Williams, 2016: The deep decarbonization pathways project (DDPP): Insights and emerging issues. *Climate Policy*, **16** (sup1), S1–S6. https://doi.org/10.1080/14693062.2016.1179620

387. Bistline, J.E., E. Hodson, C.G. Rossmann, J. Creason, B. Murray, and A.R. Barron, 2018: Electric sector policy, technological change, and U.S. emissions reductions goals: Results from the EMF 32 model intercomparison project. *Energy Economics*, **73**, 307–325. https://doi.org/10.1016/j.eneco.2018.04.012

388. Arent, D.J., P. Green, Z. Abdullah, T. Barnes, S. Bauer, A. Bernstein, D. Berry, J. Berry, T. Burrell, B. Carpenter, J. Cochran, R. Cortright, M. Curry-Nkansah, P. Denholm, V. Gevorian, M. Himmel, B. Livingood, M. Keyser, J. King, B. Kroposki, T. Mai, M. Mehos, M. Muratori, S. Narumanchi, B. Pivovar, P. Romero-Lankao, M. Ruth, G. Stark, and C. Turchi, 2022: Challenges and opportunities in decarbonizing the U.S. energy system. *Renewable and Sustainable Energy Reviews*, **169**, 112939. https://doi.org/10.1016/j.rser.2022.112939

389. Costa Jr., C., E. Wollenberg, M. Benitez, R. Newman, N. Gardner, and F. Bellone, 2022: Roadmap for achieving net-zero emissions in global food systems by 2050. *Scientific Reports*, **12** (1), 15064. https://doi.org/10.1038/s41598-022-18601-1

390. Robertson, G.P., S.K. Hamilton, K. Paustian, and P. Smith, 2022: Land-based climate solutions for the United States. *Global Change Biology*, **28** (16), 4912–4919. https://doi.org/10.1111/gcb.16267

391. Roe, S., C. Streck, M. Obersteiner, S. Frank, B. Griscom, L. Drouet, O. Fricko, M. Gusti, N. Harris, T. Hasegawa, Z. Hausfather, P. Havlík, J. House, G.-J. Nabuurs, A. Popp, M.J.S. Sánchez, J. Sanderman, P. Smith, E. Stehfest, and D. Lawrence, 2019: Contribution of the land sector to a 1.5 °C world. *Nature Climate Change*, **9** (11), 817–828. https://doi.org/10.1038/s41558-019-0591-9

392. Denholm, P., P. Brown, W. Cole, T. Mai, and B. Sergi, 2022: Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035. NREL/TP6A40-81644. U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO. https://doi.org/10.2172/1885591

393. Rosenow, J. and N. Eyre, 2022: Reinventing energy efficiency for net zero. *Energy Research & Social Science*, **90**, 102602. https://doi.org/10.1016/j.erss.2022.102602

394. IEA, 2021: Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency, Paris, France. https://www.iea.org/reports/net-zero-by-2050

395. Clark, M. and D. Tilman, 2017: Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters*, **12** (6), 064016. https://doi.org/10.1088/1748-9326/aa6cd5

396. Stehfest, E., L. Bouwman, D.P. van Vuuren, M.G.J. den Elzen, B. Eickhout, and P. Kabat, 2009: Climate benefits of changing diet. *Climatic Change*, **95** (1), 83–102. https://doi.org/10.1007/s10584-008-9534-6

397. Blair, N., C. Augustine, W. Cole, P. Denholm, W. Frazier, M. Geocaris, J. Jorgenson, K. McCabe, K. Podkaminer, A. Prasanna, and B. Sigrin, 2022: Storage Futures Study: Key Learnings for the Coming Decades. NREL/TP-7A40-81779. U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO. https://www.nrel.gov/docs/fy22osti/81779.pdf

398. Comello, S. and S. Reichelstein, 2019: The emergence of cost effective battery storage. *Nature Communications*, **10** (1), 2038. https://doi.org/10.1038/s41467-019-09988-z

399. Bistline, J., S. Bragg-Sitton, W. Cole, B. Dixon, E. Eschmann, J. Ho, A. Kwon, L. Martin, C. Murphy, C. Namovicz, and A. Sowder, 2023: Modeling nuclear energy's future role in decarbonized energy systems. i*Science*, **26** (2), 105952. https://doi.org/10.1016/j.isci.2023.105952

400. Duan, L., R. Petroski, L. Wood, and K. Caldeira, 2022: Stylized least-cost analysis of flexible nuclear power in deeply decarbonized electricity systems considering wind and solar resources worldwide. *Nature Energy*, **7** (3), 260–269. https://doi.org/10.1038/s41560-022-00979-x

401. Carton, W., A. Asiyanbi, S. Beck, H.J. Buck, and J.F. Lund, 2020: Negative emissions and the long history of carbon removal. *WIREs Climate Change*, **11** (6), e671. https://doi.org/10.1002/wcc.671

402. Fuss, S., W.F. Lamb, M.W. Callaghan, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W. de Oliveira Garcia, J. Hartmann, T. Khanna, G. Luderer, G.F. Nemet, J. Rogelj, P. Smith, J.L.V. Vicente, J. Wilcox, M. del Mar Zamora Dominguez, and J.C. Minx, 2018: Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, **13** (6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

403. Jägermeyr, J., C. Müller, A.C. Ruane, J. Elliott, J. Balkovic, O. Castillo, B. Faye, I. Foster, C. Folberth, J.A. Franke, K. Fuchs, J.R. Guarin, J. Heinke, G. Hoogenboom, T. Iizumi, A.K. Jain, D. Kelly, N. Khabarov, S. Lange, T.-S. Lin, W. Liu, O. Mialyk, S. Minoli, E.J. Moyer, M. Okada, M. Phillips, C. Porter, S.S. Rabin, C. Scheer, J.M. Schneider, J.F. Schyns, R. Skalsky, A. Smerald, T. Stella, H. Stephens, H. Webber, F. Zabel, and C. Rosenzweig, 2021: Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food*, **2** (11), 873–885. https://doi.org/10.1038/s43016-021-00400-y

404. Stehfest, E., W.-J. van Zeist, H. Valin, P. Havlik, A. Popp, P. Kyle, A. Tabeau, D. Mason-D'Croz, T. Hasegawa, B.L. Bodirsky, K. Calvin, J.C. Doelman, S. Fujimori, F. Humpenöder, H. Lotze-Campen, H. van Meijl, and K. Wiebe, 2019: Key determinants of global land-use projections. *Nature Communications*, **10** (1), 2166. https://doi.org/10.1038/s41467-019-09945-w

405. Strefler, J., E. Kriegler, N. Bauer, G. Luderer, R.C. Pietzcker, A. Giannousakis, and O. Edenhofer, 2021: Alternative carbon price trajectories can avoid excessive carbon removal. *Nature Communications*, **12** (1), 2264. https://doi.org/10.1038/s41467-021-22211-2

406. Workman, M., K. Dooley, G. Lomax, J. Maltby, and G. Darch, 2020: Decision making in contexts of deep uncertainty—An alternative approach for long-term climate policy. *Environmental Science & Policy*, **103**, 77–84. https://doi.org/10.1016/j.envsci.2019.10.002

407. Peng, W., G. Iyer, V. Bosetti, V. Chaturvedi, J. Edmonds, A.A. Fawcett, S. Hallegatte, D.G. Victor, D. van Vuuren, and J. Weyant, 2021: Climate policy models need to get real about people—Here's how. *Nature*, **594** (7862), 174–176. https://doi.org/10.1038/d41586-021-01500-2

408. Brown, M.A., P. Dwivedi, S. Mani, D. Matisoff, J.E. Mohan, J. Mullen, M. Oxman, M. Rodgers, R. Simmons, B. Beasley, and L. Polepeddi, 2021: A framework for localizing global climate solutions and their carbon reduction potential. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (31), e2100008118. https://doi.org/10.1073/pnas.2100008118

409. Daley, D.M., T.D. Abel, M. Stephan, S. Rai, and E. Rogers, 2023: Can polycentric governance lower industrial greenhouse gas emissions: Evidence from the United States. *Environmental Policy and Governance*. https://doi.org/10.1002/eet.2051

410. Hultman, N.E., Clarke, L., , C. Frisch, K. Kennedy, H. McJeon, T. Cyrs, P. Hansel, P. Bodnar, M. Manion, M.R. Edwards, R. Cui, C. Bowman, J. Lund, M.I. Westphal, A. Clapper, J. Jaeger, A. Sen, J. Lou, D. Saha, W. Jaglom, K. Calhoun, K. Igusky, J. deWeese, K. Hammoud, J.C. Altimirano, M. Dennis, C. Henderson, G. Zwicker, and J. O'Neill, 2020: Fusing subnational with national climate action is central to decarbonization: The case of the United States. *Nature Communications*, **11** (1). https://doi.org/10.1038/s41467-020-18903-w

411. Peng, W., G. Iyer, M. Binsted, J. Marlon, L. Clarke, J.A. Edmonds, and D.G. Victor, 2021: The surprisingly inexpensive cost of state-driven emission control strategies. *Nature Climate Change*, **11** (9), 738–745. https://doi.org/10.1038/s41558-021-01128-0

412. Wakiyama, T. and E. Zusman, 2021: The impact of electricity market reform and subnational climate policy on carbon dioxide emissions across the United States: A path analysis. *Renewable and Sustainable Energy Reviews*, **149**, 111337. https://doi.org/10.1016/j.rser.2021.111337

413. NC Clean Energy Technology Center, 2022: Database of State Incentives for Renewables & Efficiency. NC State University, NC Clean Energy Technology Center, accessed August 19, 2022. https://www.dsireusa.org/

414. CDP, 2023: States and Regions Climate Tracker. CDP Worldwide. https://www.cdp.net/en/research/global-reports/states-and-regions-climate-action-tracker

415. UNFCCC, 2023: Global Climate Action. United Nations Framework Convention on Climate Change. https://climateaction.unfccc.int/

416. ETC, 2018: Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors. Energy Transitions Commission. https://www.energy-transitions.org/publications/mission-possible/

417. Grubert, E. and S. Hastings-Simon, 2022: Designing the mid-transition: A review of medium-term challenges for coordinated decarbonization in the United States. *WIREs Climate Change*, **13** (3), e768. https://doi.org/10.1002/wcc.768

418. Baker, E., A.P. Goldstein, and I.M.L. Azevedo, 2021: A perspective on equity implications of net zero energy systems. *Energy and Climate Change*, **2**, 100047. https://doi.org/10.1016/j.egycc.2021.100047

419. Johnson, J.X. and J. Novacheck, 2015: Emissions reductions from expanding state-level renewable portfolio standards. *Environmental Science & Technology*, **49** (9), 5318–5325. https://doi.org/10.1021/es506123e

420. Wiser, R., T. Mai, D. Millstein, G. Barbose, L. Bird, J. Heeter, D. Keyser, V. Krishnan, and J. Macknick, 2017: Assessing the costs and benefits of US renewable portfolio standards. *Environmental Research Letters*, **12** (9), 094023. https://doi.org/10.1088/1748-9326/aa87bd

421. Young, D. and J. Bistline, 2018: The costs and value of renewable portfolio standards in meeting decarbonization goals. *Energy Economics*, **73**, 337–351. https://doi.org/10.1016/j.eneco.2018.04.017

Fifth National Climate Assessment

# Focus on Compound Events

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# Focus on Compound Events

Climate change is increasing the chances of multiple climate hazards occurring simultaneously or consecutively across the US and its territories. Such interactions between multiple hazards across space or time, known as compound events, exacerbate the societal and ecosystem impacts of individual hazards and hinder the ability of communities, particularly frontline communities, to respond and cope. Therefore, infrastructure design, planning, governance, and disaster preparedness for compound events are critical for building resilient systems.

## *What Are Compound Events?*

Compound events result from the occurrence of multiple climate drivers or hazards either in an individual location or across multiple locations that, when combined, have greater impacts than isolated hazards on ecosystems, water resources, public health, energy infrastructure, transportation, food systems, and interconnected societal networks, often straining disaster response.[1,2,3] Compound events can also result from the intersection of climate hazards with other environmental hazards like pollution, non-climate hazards such as wars and pandemics, or socioeconomic stressors like poverty and lack of adequate housing that disproportionately impact overburdened communities, thereby deepening existing societal inequities (e.g., KMs 5.2, 18.2, 20.1, 23.1, 27.1, 29.2). Compound events are broadly categorized as:

- **Multivariate**: co-occurring hazards in a location, such as simultaneous precipitation deficits and extreme heat that contributed to the severe Pan-Caribbean 2013–2016 drought[4]
- **Temporally compounding**: successive hazards in a location, such as destructive wildfires in 2017 followed by heavy rainfall on burned landscapes in January 2018 that resulted in mudslides and debris flows, damaging ecosystems and infrastructure (KMs 3.5, 5.2, 6.1, 27.2)
- **Spatially compounding**: similar or disparate hazards occurring simultaneously or within a short time window in multiple locations that are connected by physical processes or complex human and natural systems, such as simultaneous megafires across multiple western states and record back-to-back Atlantic hurricanes in 2020 that caused unprecedented demand on federal emergency response resources (Figure F1.1)[5]
- **Preconditioned**: extreme events superimposed on long-term trends, such as higher sea levels, heavier precipitation, and/or changing storm seasonality causing more frequent and severe coastal flooding (KMs 4.2, 9.1, 30.1),[6,7] like during Hurricane Florence (2018) in the Southeast (KM 22.1),[8] Typhoon Surigae (2021) in Palau, and Typhoon Merbok (2022) in Alaska (KM 29.1)[9]
- **Complex events**: non-climatic stressors that exacerbate climate hazards, such as COVID-19, which exacerbated climate-driven food, water, and livelihood insecurities facing Tribes, Indigenous Peoples, and other frontline communities (KMs 5.2, 16.1; Focus on COVID-19 and Climate Change)

## Recent Events

Compound events have resulted in multiple recent disasters across several US states. The following examples illustrate their cascading societal impacts (Figure F1.1):

- **Heat, drought, and wildfires**: A series of compound events between 2020 and 2021 stressed communities and ecosystems across the western US and caused economic damages exceeding $38.5 billion (in 2022 dollars; KMs 27.2, 28.1, 28.2, 28.4).[10] In 2020, co-occurring heat and drought caused concurrent destructive fires across California, Oregon, and Washington11 that resulted in infrastructure and property damage and human fatalities, threatened access to energy and water supplies, and strained firefighting resources.[10] Millions of residents were exposed to harmful pollutants in wildfire smoke, affecting public health and worsening COVID-19 related mortality.[12,13,14] Drought persisted into 2021 and amplified the record-breaking Northwest heatwave,[15] killing over 229 people in the US. Co-occurring heat, drought, low streamflow, and low tides in 2021 triggered toxic algal blooms and mass die-offs of shellfish and low survival of salmon, species important to Indigenous communities and the West Coast economy (KM 27.2; Figure 10.2).[16] West Coast crab fishery revenue losses were exacerbated by management actions implemented during earlier marine heatwaves.[17]
- **Compound flooding**: Back-to-back storms affected the Northeast in 2021, resulting in 55 deaths and more than $21.4 billion (in 2022 dollars) in damages (KM 21.1). On August 22, Hurricane Henri brought intense rainfall to the Northeast (7 inches in New York City, including 2 inches in one hour in Central Park) that caused $749 million (in 2022 dollars) in damages despite mild winds. On August 29, Hurricane Ida, which made landfall as a Category 4 in Louisiana, moved northeast, and delivered record rainfall during September 1–2 to already-saturated Northeast soils, causing catastrophic flooding. This temporally compounding event was about 30 times more deadly and more damaging than Hurricane Henri alone, straining local governance and emergency management systems.[18]

## Will Compound Events Increase with Climate Change?

Compound events are expected to become more frequent with continued climate change (e.g., KMs 2.2, 9.1). The increasing frequency and severity of climate hazards such as extreme heat, heavy precipitation, and severe storms are projected to increase the chances of 1) a sequence of hazards occurring within a short time span and 2) simultaneous independent events in a location or multiple locations. For instance, increasing swings from dry-to-wet extremes in western states and Pacific Islands will increase the chances of intense rains on parched or recently burned landscapes, increasing risks of postfire flash flooding, debris flow, and contaminated drinking water supplies (KMs 4.2, 30.1).[19,20,21] Climate change is also expected to alter the physical drivers of compound events. For instance, more frequent extreme La Niñas[22] would simultaneously elevate the risk of western US droughts and back-to-back severe Atlantic hurricanes, increasing the chances of compounding disasters similar to the 2020 season (Figure F1.1).[23,24] Changes in weather patterns such as more frequent atmospheric high-pressure systems could increase the risk of co-occurring heat, drought, and marine heatwaves.[25,26]

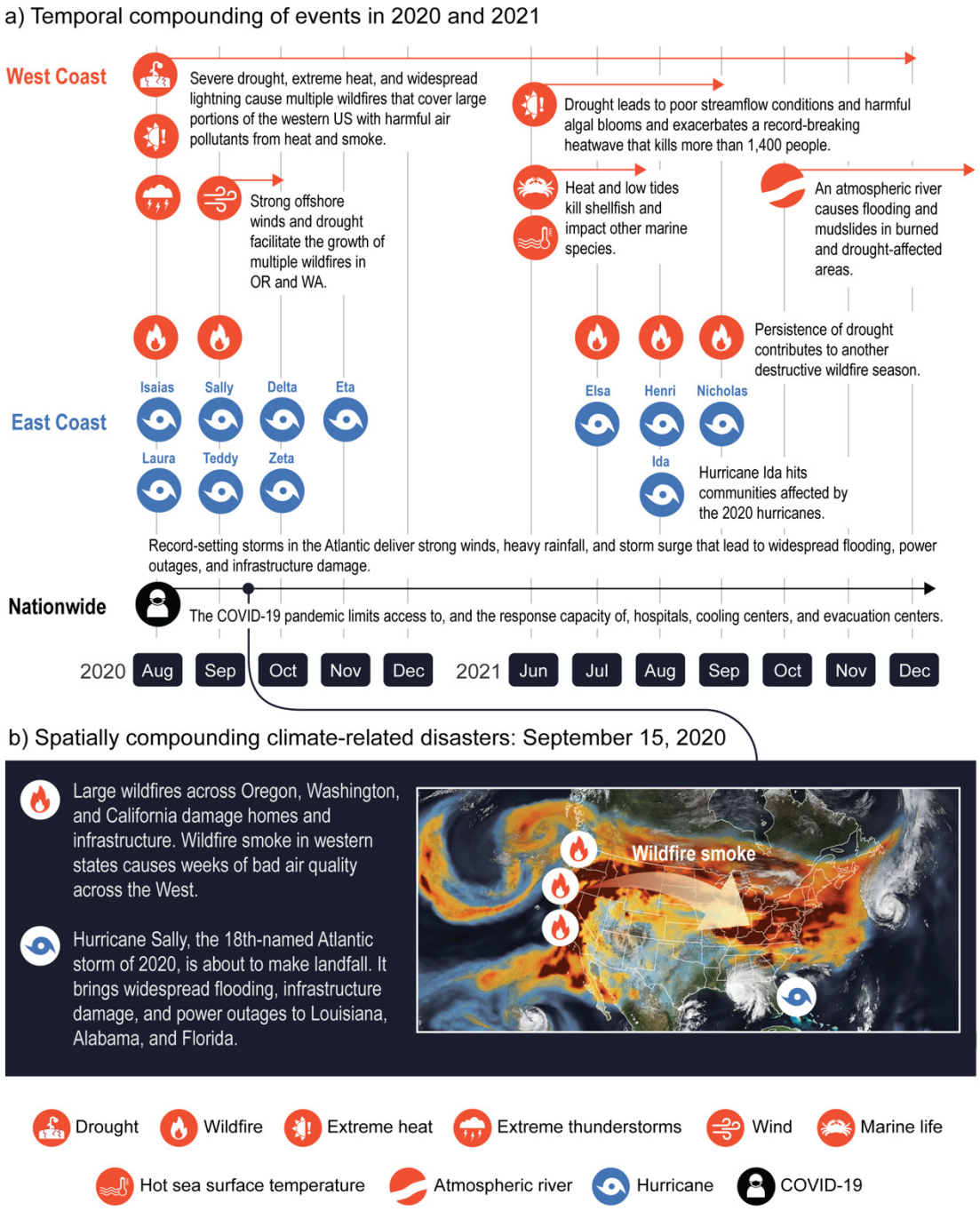
## How Can We Adapt?

Low-income communities, communities of color, Tribes and Indigenous Peoples experience high exposure and vulnerability to climate hazards due to their proximity to hazard-prone areas, infrastructure deficits, limited disaster-management resources, and governance challenges, which are legacies of colonialism, redlining, and other discriminatory policies (KMs 4.2, 16.2, 18.2, 20.1).[27] Consequently, these communities could face higher risks through complex event outcomes, which can magnify existing disproportionate health risks (KM 15.2). Transformative, socially just adaptation approaches (KM 31.3), investment in emergency preparedness, and governance structures that account for the inequitable distribution of climate impacts can avoid further exacerbating such existing social disparities (KMs 12.4, 20.3, 31.2).[28,29,30] Incorporat-

ing compound event risks in infrastructure design standards and regulations, updating aging infrastructure, and planning at the community-level can improve climate resilience and protect against risks like displacement and gentrification.[28,31,32] Despite the availability of tools to evaluate infrastructure alternatives (e.g., Helgeson et al. 2020[33]), communities with limited adaptation resources face significant challenges in making such investments.

Resource allocation toward solutions that address multiple community resilience objectives can address some of these challenges.[34,35] For example, blue-green infrastructure—use of green-areas and water bodies in urban planning—and tidal marsh restoration can sequester greenhouse gas emissions and protect against floods while also providing ecosystem services like reducing heat and air pollution, creating recreational spaces, and advancing environmental justice in urban environments (KM 12.3).[36] Enhanced monitoring of adaptation actions, scenario planning activities (e.g., Gerlak et al. 2021[37]), and sharing best practices among stakeholders can alleviate planning challenges and improve management of the growing risk of compound events.

## Compound Events




**Compound events have amplifying impacts on ecosystems and human communities and affect their capacity to respond.**

**Figure F1.1.** (**a**) The timeline shows temporally compounding events in 2020–2021 on the West and East Coasts and their cascading impacts on communities and ecosystems. (**b**) The satellite image shows simultaneous disasters—multiple wildfires in the US West and Hurricane Sally in the Southeast. The orange and red colors show wildfire smoke traveling across the US. Figure credit: Washington State University Vancouver. See figure metadata for additional contributors. Satellite image credit: Joshua Stevens, NASA Earth Observatory, using GEOS-5 data courtesy of NASA GSFC and VIIRS data courtesy of NASA EOSDIS/LANCE and GIBS/Worldview and the Suomi National Polar-orbiting Partnership.

# Traceable Accounts

## *Description of Evidence Base and Research Gaps*

There is broad agreement across the physical and social sciences and engineering communities that compound events are a growing threat to communities, sectors, emergency management, insurance companies, and interconnected societal systems. Recent studies have developed frameworks for studying compound events and quantified future changes in risks in several types of compound events such as hot and dry or hot and humid extremes, compound coastal and fluvial flooding, drought and marine heatwaves, marine heatwaves and ocean acidity extremes, and wildfires followed by heavy rainfall. Identification of various types of compound events has grown in recent years. Compound events are rare, and thus the short observational record for many climate variables limits the ability to quantify historical changes, characterize present-day probabilities, and evaluate the ability of climate models to simulate them. There are also gaps in the scientific understanding of the range of physical processes that lead to various types of compound events affecting many regions, communities, and sectors. Literature on their societal impacts is even more limited and challenging to quantify because compound events are still relatively rare and result from a complex set of factors. Together, these result in uncertainties and low confidence in estimates of projected changes in their risks.

Compound events span a wide variety of physical phenomena, societal impacts, and different research communities with different needs, requirements, and impacts. There is a diversity of definitions of compound events, and much of the literature consists of case studies. Compound events of multiple weather and climate variables are often treated by combining those variables into a single metric. For instance, the literature contains multiple formulations of the combined effect of high temperatures, humidity (or aridity), and winds (or stagnancy) on human health and fire risk. While such univariate formulations are more amenable to standard analysis techniques, the richness of the multivariate space can be lost. Advanced multivariate extreme statistical analysis tools have not seen widespread adoption by the scientific community. The recent development of large climate model ensembles combined with event identification analysis tools offers the opportunity to increase our understanding of the physical processes that lead to compound events and to evaluate their historical and future risks under different warming levels.

# References


1. Kuhla, K., S.N. Willner, C. Otto, T. Geiger, and A. Levermann, 2021: Ripple resonance amplifies economic welfare loss from weather extremes. *Environmental Research Letters*, **16** (11), 114010. https://doi.org/10.1088/1748-9326/ac2932

2. Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A.D. Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, 2021: Ch. 11. Weather and climate extreme events in a changing climate. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1513–1766. https://doi.org/10.1017/9781009157896.013

3. Zscheischler, J., O. Martius, S. Westra, E. Bevacqua, C. Raymond, R.M. Horton, B. van den Hurk, A. AghaKouchak, A. Jézéquel, M.D. Mahecha, D. Maraun, A.M. Ramos, N.N. Ridder, W. Thiery, and E. Vignotto, 2020: A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, **1** (7), 333–347. https://doi.org/10.1038/s43017-020-0060-z

4. Herrera, D.A., T.R. Ault, J.T. Fasullo, S.J. Coats, C.M. Carrillo, B.I. Cook, and A.P. Williams, 2018: Exacerbation of the 2013–2016 pan-Caribbean drought by anthropogenic warming. *Geophysical Research Letters*, **45** (19), 10619–10626. https://doi.org/10.1029/2018GL079408

5. FEMA, 2021: 2022–2026 FEMA Strategic Plan: Building the FEMA Our Nation Needs and Deserves. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/about/strategic-plan

6. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

7. Taherkhani, M., S. Vitousek, P.L. Barnard, N. Frazer, T.R. Anderson, and C.H. Fletcher, 2020: Sea-level rise exponentially increases coastal flood frequency. *Scientific Reports*, **10** (1), 6466. https://doi.org/10.1038/s41598-020-62188-4

8. Reed, K.A., A.M. Stansfield, M.F. Wehner, and C.M. Zarzycki, 2020: Forecasted attribution of the human influence on Hurricane Florence. *Science Advances*, **6** (1), 9253. https://doi.org/10.1126/sciadv.aaw9253

9. Fang, Z., P.T. Freeman, C.B. Field, and K.J. Mach, 2018: Reduced sea ice protection period increases storm exposure in Kivalina, Alaska. *Arctic Science*, **4** (4), 525–537. https://doi.org/10.1139/as-2017-0024

10. NCEI, 2022: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

11. Abatzoglou, J.T., C.S. Juang, A.P. Williams, C.A. Kolden, and A.L. Westerling, 2021: Increasing synchronous fire danger in forests of the western United States. *Geophysical Research Letters*, **48** (2), e2020GL091377. https://doi.org/10.1029/2020gl091377

12. Kalashnikov, D.A., J.L. Schnell, J.T. Abatzoglou, D.L. Swain, and D. Singh, 2022: Increasing co-occurrence of fine particulate matter and ground-level ozone extremes in the western United States. *Science Advances*, **8** (1), 9386. https://doi.org/10.1126/sciadv.abi9386

13. Liu, Y., E. Austin, J. Xiang, T. Gould, T. Larson, and E. Seto, 2021: Health impact assessment of the 2020 Washington state wildfire smoke episode: Excess health burden attributable to increased $PM_{2.5}$ exposures and potential exposure reductions. *GeoHealth*, **5** (5), e2020GH000359. https://doi.org/10.1029/2020gh000359

14. Zhou, X., K. Josey, L. Kamareddine, M.C. Caine, T. Liu, L.J. Mickley, M. Cooper, and F. Dominici, 2021: Excess of COVID-19 cases and deaths due to fine particulate matter exposure during the 2020 wildfires in the United States. *Science Advances*, **7** (33), 8789. https://doi.org/10.1126/sciadv.abi8789

15. Bartusek, S., K. Kornhuber, and M. Ting, 2022: 2021 North American heatwave amplified by climate change-driven nonlinear interactions. *Nature Climate Change*, **12** (12), 1143–1150. https://doi.org/10.1038/s41558-022-01520-4

16. Raymond, W.W., J.S. Barber, M.N. Dethier, H.A. Hayford, C.D.G. Harley, T.L. King, B. Paul, C.A. Speck, E.D. Tobin, A.E.T. Raymond, and P.S. McDonald, 2022: Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. *Ecology*, **103** (10), e3798. https://doi.org/10.1002/ecy.3798

17. Seary, R., J.A. Santora, D. Tommasi, A. Thompson, S.J. Bograd, K. Richerson, S. Brodie, and D. Holland, 2022: Revenue loss due to whale entanglement mitigation and fishery closures. *Scientific Reports*, **12** (1), 21554. https://doi.org/10.1038/s41598-022-24867-2

18. Jerolleman, A., S. Laska, and J. Torres, 2021: Lessons from Concurrent Disasters: COVID-19 and Eight Hurricanes. Natural Hazards Center Quick Response Grant Report Series, 327. University of Colorado Boulder, Natural Hazards Center, Boulder, CO. https://hazards.colorado.edu/quick-response-report/lessons-from-co-occurring-disasters

19. Paul, M.J., S.D. LeDuc, M.G. Lassiter, L.C. Moorhead, P.D. Noyes, and S.G. Leibowitz, 2022: Wildfire induces changes in receiving waters: A review with considerations for water quality management. *Water Resources Research*, **58** (9), e2021WR030699. https://doi.org/10.1029/2021wr030699

20. Touma, D., S. Stevenson, D.L. Swain, D. Singh, D.A. Kalashnikov, and X. Huang, 2022: Climate change increases risk of extreme rainfall following wildfire in the western United States. *Science Advances*, **8** (13), 0320. https://doi.org/10.1126/sciadv.abm0320

21. Swain, D.L., B. Langenbrunner, J.D. Neelin, and A. Hall, 2018: Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change*, **8** (5), 427–433. https://doi.org/10.1038/s41558-018-0140-y

22. Cai, W., A. Santoso, M. Collins, B. Dewitte, C. Karamperidou, J.-S. Kug, M. Lengaigne, M.J. McPhaden, M.F. Stuecker, A.S. Taschetto, A. Timmermann, L. Wu, S.-W. Yeh, G. Wang, B. Ng, F. Jia, Y. Yang, J. Ying, X.-T. Zheng, T. Bayr, J.R. Brown, A. Capotondi, K.M. Cobb, B. Gan, T. Geng, Y.-G. Ham, F.-F. Jin, H.-S. Jo, X. Li, X. Lin, S. McGregor, J.-H. Park, K. Stein, K. Yang, L. Zhang, and W. Zhong, 2021: Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment*, **2** (9), 628–644. https://doi.org/10.1038/s43017-021-00199-z

23. Marlon, J.R., P.J. Bartlein, D.G. Gavin, C.J. Long, R.S. Anderson, C.E. Briles, K.J. Brown, D. Colombaroli, D.J. Hallett, M.J. Power, E.A. Scharf, and M.K. Walsh, 2012: Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (9), E535–E543. https://doi.org/10.1073/pnas.1112839109

24. Steptoe, H., S.E.O. Jones, and H. Fox, 2018: Correlations between extreme atmospheric hazards and global teleconnections: Implications for multihazard resilience. *Reviews of Geophysics*, **56** (1), 50–78. https://doi.org/10.1002/2017rg000567

25. Loikith, P.C., D. Singh, and G.P. Taylor, 2022: Projected changes in atmospheric ridges over the Pacific–North American region using CMIP6 models. *Journal of Climate*, **35** (15), 5151–5171. https://doi.org/10.1175/jcli-d-21-0794.1

26. Shi, H., M. García-Reyes, M.G. Jacox, R.R. Rykaczewski, B.A. Black, S.J. Bograd, and W.J. Sydeman, 2021: Co-occurrence of California drought and northeast Pacific marine heatwaves under climate change. *Geophysical Research Letters*, **48** (17), e2021GL092765. https://doi.org/10.1029/2021gl092765

27. NAACP, 2021: Core Principles of Equity and Emergency Management. National Association for the Advancement of Colored People. https://naacp.org/resources/core-principles-equity-and-emergency-management

28. Jerolleman, A., 2019: *Disaster Recovery Through the Lens of Justice*. Palgrave Pivot, Cham, Switzerland, 108 pp. https://doi.org/10.1007/978-3-030-04795-5

29. Kruczkiewicz, A., M. Braun, S. McClain, H. Greatrex, L. Padilla, L. Hoffman-Hernandez, K. Siahaan, M. Nielsen, B. Llamanzares, and Z. Flamig, 2021: Ch. 16. Flood risk and monitoring data for preparedness and response. In: *Global Drought and Flood: Observation, Modeling, and Prediction*. Wu, H., D.P. Lettenmaier, Q. Tang, and P.J. Ward, Eds. American Geophysical Union, 289–306. https://doi.org/10.1002/9781119427339.ch16

30. van den Hurk, B.J.J.M., C.J. White, A.M. Ramos, P.J. Ward, O. Martius, I. Olbert, K. Roscoe, H.M.D. Goulart, and J. Zscheischler, 2023: Consideration of compound drivers and impacts in the disaster risk reduction cycle. *iScience*, **26** (3). https://doi.org/10.1016/j.isci.2023.106030

31. Helgeson, J. and J. Li, 2022: New ways to get to high ground. *Issues in Science and Technology*, **38** (2), 64–67. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=933784

32. The World Bank, 2016: Building Regulation for Resilience: Managing Risks for Safer Cities. World Bank Group. https://www.gfdrr.org/en/publication/building-regulation-resilience-managing-risks-safer-cities

33. Helgeson, J., D. Webb, and P. Lavappa, 2020: EDGe$ (Economic Decision Guide Software) Online Tool. National Institute of Standards and Technology. https://www.nist.gov/services-resources/software/edge-economic-decision-guide-software-online-tool

34. Fung, J.F. and J.F. Helgeson, 2017: Defining the Resilience Dividend: Accounting for Co-benefits of Resilience Planning. NIST Technical Note 1959. U.S. Department of Commerce, National Institute of Standards and Technology. https://doi.org/10.6028/nist.tn.1959

35. Helgeson, J. and C. O'Fallon, 2021: Resilience dividends and resilience windfalls: Narratives that tie disaster resilience co-benefits to long-term sustainability. *Sustainability*, **13** (8), 4554. https://doi.org/10.3390/su13084554

36. Narayan, S., M.W. Beck, P. Wilson, C.J. Thomas, A. Guerrero, C.C. Shepard, B.G. Reguero, G. Franco, J.C. Ingram, and D. Trespalacios, 2017: The value of coastal wetlands for flood damage reduction in the northeastern USA. *Scientific Reports*, **7** (1), 9463. https://doi.org/10.1038/s41598-017-09269-z

37. Gerlak, A.K., K.L. Jacobs, A.L. McCoy, S. Martin, M. Rivera-Torres, A.M. Murveit, A.J. Leinberger, and T. Thomure, 2021: Scenario planning: Embracing the potential for extreme events in the Colorado River Basin. *Climatic Change*, **165** (1), 27. https://doi.org/10.1007/s10584-021-03013-3

Fifth National Climate Assessment

# Focus on Western Wildfires

# Focus on Western Wildfires

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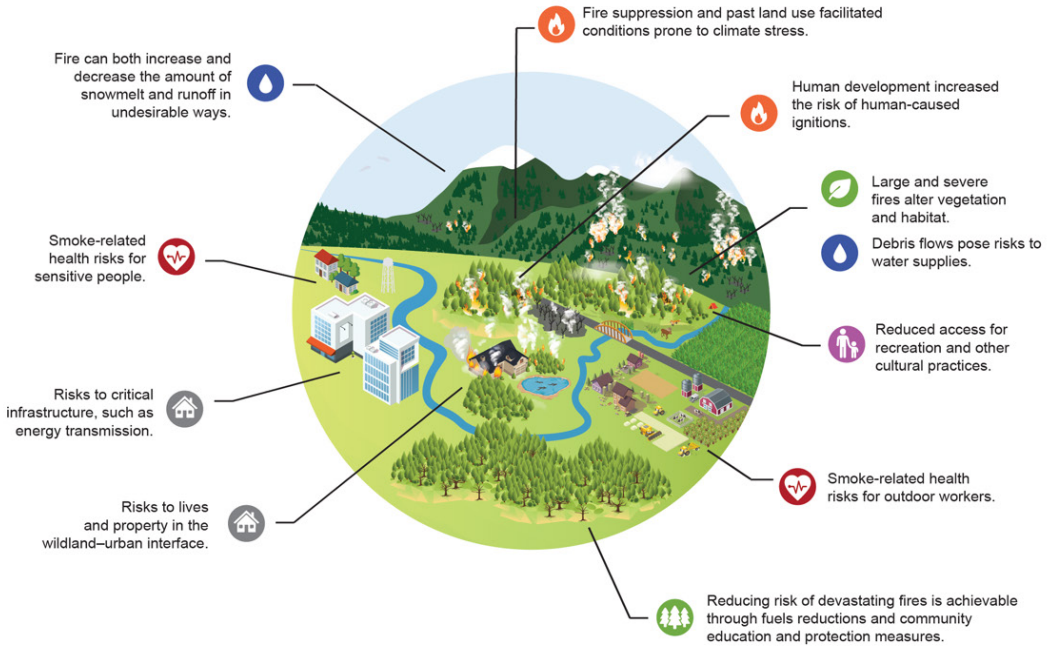
# Focus on Western Wildfires

Climate change is leading to larger and more severe wildfires in the western United States, bringing acute and chronic impacts both near and far from the flames. These wildfires have significant public health, socioeconomic, and ecological implications for the Nation.

Fire is a critical ecosystem process across the western US. In recent decades, wildfires in the western United States have become larger, hotter, and more destructive and deadly due to a suite of factors, including climate change. Prior to federal policy to suppress wildfires, natural wildfire and Indigenous burning ensured that landscapes benefited from regular fires for millennia (KM 28.5).[1] Nineteenth- and early-20th-century land-use practices, followed by a policy of fire elimination, led to vegetation fuel buildup in low-elevation fire-adapted western forests, and livestock grazing promoted highly flammable annual grass dominance in rangelands (KMs 2.2, 7.1, 28.5).[2,3,4] Development in the last 50 years has greatly expanded the wildland–urban interface (KMs 12.2, 28.5)[5] and increased human-caused ignitions, jeopardizing people, property, and infrastructure.[6,7] In recent years, climate change has contributed to very large and severe fires. While low- and moderate-severity fire with small patches of high severity can have important ecological benefits (Chs. 7, 28), large, high-severity fires often have profoundly negative long-term ecological, social, and economic consequences (Figure F2.1; KM 28.4).[8,9]

## Wildfire Impacts




### Wildfire: Causes and drivers

Warming, shifts in precipitation, and a drier near-surface atmosphere are increasing the frequency of large fires and the area burned (KMs 2.2, 7.1).

Fire exclusion and past management in dry forests have increased climatic stress and fire risk (KM 28.5).

### Risks: Water

Particulates from wildfires reduce the albedo of snow and can accelerate snowmelt, influencing water retention and runoff (KM 28.5).

Burned areas are a debris-flow risk and threaten water supplies through erosion and particulates from smoke (KM 3.4).

### Risks: Society and culture

Burned areas reduce access for recreation and other cultural uses (KMs 16.1, 28.5).

Wildfire generates substantial economic impacts, from whole sectors to individuals (KM 19.1).

### Risks: Ecosystems

Large burned areas, especially with high fire severity, can promote vegetation and habitat changes (KMs 6.1, 7.2, 8.1, 8.2).

### Risks: Built environment

Risks to critical infrastructure, energy, and water storage (KM 6.1).

Risks to personal safety and property and higher insurance costs for people living in the wildland–urban interface (KM 5.1).

### Risks: Health

Smoke can be transported thousands of miles; airborne particulate matter creates health risks, especially for those with existing health conditions, older adults, and children (KMs 14.2, 15.1, 28.4).

Smoke and long periods of degraded air quality create health risks for outdoor workers and firefighters (KM 28.4) and disproportionately affect vulnerable populations (KM 27.5).

### Opportunities: Management and adaptation

Adaptation of management strategies that create, maintain, and restore resilient forest ecosystems are critical to maintaining equitable provisioning of ecosystem services (KMs 7.3, 28.5, 31.1).

**Climate change has increased the area burned and severity of wildfires and impacts on the environment, human health, and society.**

**Figure F2.1.** Indicators and risks illustrate the drivers of, impacts from, and solutions to wildfire across a range of socioecological contexts within and beyond the western states. Considering these helps improve understanding of how impacts are experienced and how to adapt. Figure credit: USDA ARS, USDA Forest Service, University of Washington, and Montana Health Professionals for a Healthy Climate.

Climate change has produced warmer and drier conditions with prolonged droughts that stress forest vegetation, facilitating pest outbreaks and tree death, leading to the accumulation of surface fuel.[10,11] Wildfires are moving up in elevation, due to warming temperatures, reduced snowpacks and summer precipitation, and overall drier conditions (KMs 2.2, 3.5, 7.1, 28.5). Climate change has also increased vapor pressure deficit that dries fuels, altering fire behavior that results in large, hotter, and more severe fires (KMs 7.1, 28.5).[12,13,14,15] Consequently, the annual area burned and area burned by high-severity wildfires have increased in the West about eightfold since 1985 (Ch. 7).[14,16] And while the annual area burned is on par with pre-European settlement, the very large, high-severity, and deadly and destructive wildfires result in significant socioecological and economic impacts. These trends are expected to continue at least to midcentury, when fuel availability is expected to become more limited in some western forests (KMs 3.5, 28.5).[17]

In some non-forested regions, primarily arid shrublands and steppes, changes in the frequency and extent of wildfires are being driven primarily by invasive annual grasses that have benefited from climate change.[2,18] Intermountain West steppe rangelands are among the most threatened ecosystems in the US due to land use and wildfires, which have become larger and more frequent.[19] In oak savanna and chaparral shrublands, historical increases in fire are linked to changes in human ignitions and land use.[7,20]

Further increases in area burned and wildfire severity are expected to alter the distribution and abundance of plants and animals and lead to biodiversity loss (KM 7.1). In some cases, forested areas that experienced repeated severe reburns have transitioned to shrublands or other vegetation types.[21,22,23] Already, approximately 75% of vegetation type conversion in the Southwest is due to high-severity fire.[24] Continued warming, reductions in precipitation in some areas, and more frequent fire in forest and non-forest ecosystems can facilitate the establishment of invasive species, increase fuel flammability, reduce tree regeneration after wildfires,[18,25,26] and alter vegetation types (KMs 7.5, 28.5).[27] Potential reductions in forest and shrub cover due to climate-driven changes and wildfire reduce the potential for some western forestlands and steppe rangelands to function as carbon sinks (KM 7.2).

Although restored fire regimes can benefit forest hydrology in some cases,[28] wildfires can put critical infrastructure at risk by altering soil conditions and water runoff (KM 6.1). Following fire, intense rain on water-repellent soils can cause debris flows, which cause human deaths, property damage, and costly road closures (KM 6.1).[29] Chemical runoff can contaminate water supplies, and excess sediment runoff can reduce reservoir storage capacity.[30,31,32] Soot from fire emissions also darkens the surface of snow and ice, altering snow retention and melt in potentially undesirable ways.[33,34]

Human infrastructure can also affect wildfire risk. Although uncommon, fires caused by electrical transmission lines have been large and deadly. The 2018 Camp Fire nearly destroyed the entire town of Paradise, California, displacing tens of thousands of residents,[35] many of whom have not returned. To reduce such ignitions, electrical grid power shutoffs are used during windy weather.[36] However, this approach can disrupt local economies (e.g., agriculture and healthcare) and livelihoods, with disproportionately high impacts on rural and overburdened communities.[37]

Wildfire smoke can be transported thousands of miles, causing significant environmental, public health, and socioeconomic impacts across the country (KMs 14.1, 19.1, 25.1).[38,39] Smoke from burning vegetation and built structures contains fine particulate matter ($PM_{2.5}$), ozone precursors, and other toxic components (KM 14.2).[40] Although the annual average level of $PM_{2.5}$ has declined over recent decades due to air quality policies, the frequency and severity of smoke events in the western US make wildfire the largest contributor to $PM_{2.5}$ in this region, offsetting some of those improvements (KM 14.1). Exposure to wildfire smoke is associated with adverse cardiovascular and respiratory outcomes (KM 15.1), as well as increased risks of

COVID-19 mortality (Focus on COVID-19 and Climate Change).[41,42] Wildfire smoke may also affect neonatal human health, such as lower birthweights or pregnancy loss.[43,44]

Projected changes in wildfire are expected to result in a significant health burden, especially for at-risk populations.[45] Susceptibility to wildfire smoke exposure can be exacerbated by age, preexisting health conditions, socioeconomic status, occupation, and housing status (e.g., people who are unhoused experience constant exposure). Wildland firefighters are at increased risk of lung cancer mortality and cardiovascular diseases.[46] Where wildfires overlap with harvest seasons, farmworkers and other outdoor workers (frequently low-income workers from immigrant and Indigenous communities) are at risk (KMs 14.2, 15.2, 16.1, 27.1, 28.4).

Enhancing ecosystem resilience and protecting communities from wildfires is achievable through investments in both ecosystems and social systems (KM 28.5). Proactive actions include strategically placing forest fuel treatments in high-fire-risk locations and accelerating vegetation management, including the use of fire at ecologically meaningful spatial scales. These actions often require surface and ladder fuel reductions through prescribed burning or mechanical removal[47] and allowing low-intensity wildfires to burn in strategic locations (KMs 7.3, 28.5). In fire-adapted ecosystems, low- and moderate-severity wildfires reduce smaller trees, shrubs, and dead fuels, maintaining forests with fewer, more widely spaced trees (KMs 7.3, 28.5), thus increasing resilience to future climate impacts. Burned area rehabilitation efforts can reduce sediment runoff and protect water supply and hydroelectrical infrastructure (KMs 5.1, 7.1).

Efforts to strategically reduce the number of human-caused ignitions and investments in home hardening are important adaptation measures in some areas.[7,20] Fireproofing structures and other design and construction efforts can reduce the likelihood of structure ignition, lessening wildfire risk to communities.[48] Land and community planning practices—including zoning, ordinances, and building codes—influence wildfire risks to homes in wildfire-prone regions.[49] Additional measures for protecting communities involve improvements in data access and usability, emergency response planning, healthcare system preparedness, and early-warning systems for evacuation and timely communication of health impacts to the public, especially for at-risk populations and outdoor workers (KMs 14.1, 19.3).

# Traceable Accounts

## *Description of Evidence Base and Research Gaps*

This focus box examines observed and projected wildfire trends for western North America and the impacts of wildfire nationally.[3,38,50] This includes research that has used remotely sensed and modeled data, alongside field-based experimental and observational data, to demonstrate that the influence of climate change on current and future wildfire is through warming temperatures, which have reduced fuel moisture content and made the fuels more flammable.[11,12,14,22] Research demonstrates that roughly half of the increase in area burned is due to increases in fuel flammability as a result of anthropogenic climate change (KMs 3.5, 7.1).[12] Warming, lowered humidity, and atmospheric drying (i.e., higher vapor pressure deficit) have facilitated increases in the frequency of fire-conducive weather as well as of annual area burned and the proportion burned at high severity by wildfire (KM 2.2).[14,16] Similar methods have also been used to elucidate factors influencing wildfire smoke pollutant mixture and the effects on human health.[38,39,42]

There is strong and building evidence that reducing forest fuels and lowering the density of trees in forests lessens the impact of climate-mediated stress and disturbance.[4] Greater resistance and resilience to wildfire can be achieved through mechanical vegetation treatments with the use of prescribed fire and managed wildfire (KMs 7.3, 28.5). An increased and refined understanding of appropriate adaptation strategies to safeguard ecosystems, communities, and people could enhance outcomes of future investments.[4] There is evidence that planning, zoning, updating building codes, and fireproofing structures can mitigate risk and losses to infrastructure and property.[48,49] Key areas of future investigation include, but are not limited to, the appropriate suite of land-based practices (i.e., thinning, prescribed fire) as well as the ecosystem specificity (e.g., forest or vegetation type) and the appropriate spatial scale needed to meaningfully reduce risk.[15] Lastly, an increased understanding of the composition of rural populations in the western US, how different subsets of the population access information, and behavioral responses to wildfire-related alerts would allow for more targeted messaging and more informed allocation of resources during wildfire and smoke events.[45]

# References


1. Margolis, E.Q., C.H. Guiterman, R.D. Chavardès, J.D. Coop, K. Copes-Gerbitz, D.A. Dawe, D.A. Falk, J.D. Johnston, E. Larson, H. Li, J.M. Marschall, C.E. Naficy, A.T. Naito, M.-A. Parisien, S.A. Parks, J. Portier, H.M. Poulos, K.M. Robertson, J.H. Speer, M. Stambaugh, T.W. Swetnam, A.J. Tepley, I. Thapa, C.D. Allen, Y. Bergeron, L.D. Daniels, P.Z. Fulé, D. Gervais, M.P. Girardin, G.L. Harley, J.E. Harvey, K.M. Hoffman, J.M. Huffman, M.D. Hurteau, L.B. Johnson, C.W. Lafon, M.K. Lopez, R.S. Maxwell, J. Meunier, M. North, M.T. Rother, M.R. Schmidt, R.L. Sherriff, L.A. Stachowiak, A. Taylor, E.J. Taylor, V. Trouet, M.L. Villarreal, L.L. Yocom, K.B. Arabas, A.H. Arizpe, D. Arseneault, A.A. Tarancón, C. Baisan, E. Bigio, F. Biondi, G.D. Cahalan, A. Caprio, J. Cerano-Paredes, B.M. Collins, D.C. Dey, I. Drobyshev, C. Farris, M.A. Fenwick, W. Flatley, M.L. Floyd, Z.e. Gedalof, A. Holz, L.F. Howard, D.W. Huffman, J. Iniguez, K.F. Kipfmueller, S.G. Kitchen, K. Lombardo, D. McKenzie, A.G. Merschel, K.L. Metlen, J. Minor, C.D. O'Connor, L. Platt, W.J. Platt, T. Saladyga, A.B. Stan, S. Stephens, C. Sutheimer, R. Touchan, and P.J. Weisberg, 2022: The North American tree-ring fire-scar network. *Ecosphere*, **13** (7), e4159. https://doi.org/10.1002/ecs2.4159

2. D'Antonio, C.M. and P.M. Vitousek, 1992: Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology and Systematics*, **23** (1), 63–87. https://doi.org/10.1146/annurev.es.23.110192.000431

3. Hagmann, R.K., P.F. Hessburg, S.J. Prichard, N.A. Povak, P.M. Brown, P.Z. Fulé, R.E. Keane, E.E. Knapp, J.M. Lydersen, K.L. Metlen, M.J. Reilly, A.J. Sánchez Meador, S.L. Stephens, J.T. Stevens, A.H. Taylor, L.L. Yocom, M.A. Battaglia, D.J. Churchill, L.D. Daniels, D.A. Falk, P. Henson, J.D. Johnston, M.A. Krawchuk, C.R. Levine, G.W. Meigs, A.G. Merschel, M.P. North, H.D. Safford, T.W. Swetnam, and A.E.M. Waltz, 2021: Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecological Applications*, **31** (8), e02431. https://doi.org/10.1002/eap.2431

4. Hessburg, P.F., C.L. Miller, S.A. Parks, N.A. Povak, A.H. Taylor, P.E. Higuera, S.J. Prichard, M.P. North, B.M. Collins, M.D. Hurteau, A.J. Larson, C.D. Allen, S.L. Stephens, H. Rivera-Huerta, C.S. Stevens-Rumann, L.D. Daniels, Z.e. Gedalof, R.W. Gray, V.R. Kane, D.J. Churchill, R.K. Hagmann, T.A. Spies, C.A. Cansler, R.T. Belote, T.T. Veblen, M.A. Battaglia, C. Hoffman, C.N. Skinner, H.D. Safford, and R.B. Salter, 2019: Climate, environment, and disturbance history govern resilience of western North American forests. *Frontiers in Ecology and Evolution*, **7**, 239. https://doi.org/10.3389/fevo.2019.00239

5. Radeloff, V.C., D.P. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar-Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, and S.I. Stewart, 2018: Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (13), 3314–3319. https://doi.org/10.1073/pnas.1718850115

6. Chen, B. and Y. Jin, 2022: Spatial patterns and drivers for wildfire ignitions in California. *Environmental Research Letters*, **17** (5), 055004. https://doi.org/10.1088/1748-9326/ac60da

7. Keeley, J.E. and A.D. Syphard, 2018: Historical patterns of wildfire ignition sources in California ecosystems. *International Journal of Wildland Fire*, **27** (12), 781–799. https://doi.org/10.1071/wf18026

8. UNEP, 2022: Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires. A UNEP Rapid Response Assessment. United Nations Environment Programme, Nairobi, Kenya. https://www.unep.org/resources/report/spreading-wildfire-rising-threat-extraordinary-landscape-fires

9. Coop, J.D., S.A. Parks, C.S. Stevens-Rumann, S.D. Crausbay, P.E. Higuera, M.D. Hurteau, A. Tepley, E. Whitman, T. Assal, B.M. Collins, K.T. Davis, S. Dobrowski, D.A. Falk, P.J. Fornwalt, P.Z. Fulé, B.J. Harvey, V.R. Kane, C.E. Littlefield, E.Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K.C. Rodman, 2020: Wildfire-driven forest conversion in western North American landscapes. *BioScience*, **70** (8), 659–673. https://doi.org/10.1093/biosci/biaa061

10. Fettig, C.J., C. Asaro, J.T. Nowak, K.J. Dodds, K.J.K. Gandhi, J.E. Moan, and J. Robert, 2022: Trends in bark beetle impacts in North America during a period (2000–2020) of rapid environmental change. *Journal of Forestry*, **120** (6), 693–713. https://doi.org/10.1093/jofore/fvac021

11. Goulden, M.L. and R.C. Bales, 2019: California forest die-off linked to multi-year deep soil drying in 2012–2015 drought. *Nature Geoscience*, **12** (8), 632–637. https://doi.org/10.1038/s41561-019-0388-5

12. Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (42), 11770–11775. https://doi.org/10.1073/pnas.1607171113

13. Mueller, S.E., A.E. Thode, E.Q. Margolis, L.L. Yocom, J.D. Young, and J.M. Iniguez, 2020: Climate relationships with increasing wildfire in the southwestern US from 1984 to 2015. *Forest Ecology and Management*, **460**, 117861. https://doi.org/10.1016/j.foreco.2019.117861

14. Parks, S.A. and J.T. Abatzoglou, 2020: Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters*, **47** (22), e2020GL089858. https://doi.org/10.1029/2020gl089858

15. Stephens, S.L., A.A. Bernal, B.M. Collins, M.A. Finney, C. Lautenberger, and D. Saah, 2022: Mass fire behavior created by extensive tree mortality and high tree density not predicted by operational fire behavior models in the southern Sierra Nevada. *Forest Ecology and Management*, **518**, 120258. https://doi.org/10.1016/j.foreco.2022.120258

16. Williams, J.N., H.D. Safford, N. Enstice, Z.L. Steel, and A.K. Paulson, 2023: High-severity burned area and proportion exceed historic conditions in Sierra Nevada, California, and adjacent ranges. *Ecosphere*, **14** (1), e4397. https://doi.org/10.1002/ecs2.4397

17. Abatzoglou, J.T., D.S. Battisti, A.P. Williams, W.D. Hansen, B.J. Harvey, and C.A. Kolden, 2021: Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth & Environment*, **2** (1), 227. https://doi.org/10.1038/s43247-021-00299-0

18. Kerns, B.K., C. Tortorelli, M.A. Day, T. Nietupski, A.M.G. Barros, J.B. Kim, and M.A. Krawchuk, 2020: Invasive grasses: A new perfect storm for forested ecosystems? *Forest Ecology and Management*, **463**, 117985. https://doi.org/10.1016/j.foreco.2020.117985

19. Bradley, B.A., C.A. Curtis, E.J. Fusco, J.T. Abatzoglou, J.K. Balch, S. Dadashi, and M.-N. Tuanmu, 2018: Cheatgrass (*Bromus tectorum*) distribution in the intermountain Western United States and its relationship to fire frequency, seasonality, and ignitions. *Biological Invasions*, **20** (6), 1493–1506. https://doi.org/10.1007/s10530-017-1641-8

20. Syphard, A.D., J.E. Keeley, M. Gough, M. Lazarz, and J. Rogan, 2022: What makes wildfires destructive in California? *Fire*, **5** (5). https://doi.org/10.3390/fire5050133

21. Hayes, K. and B. Buma, 2021: Effects of short-interval disturbances continue to accumulate, overwhelming variability in local resilience. *Ecosphere*, **12** (3), e03379. https://doi.org/10.1002/ecs2.3379

22. Lydersen, J.M., B.M. Collins, M. Coppoletta, M.R. Jaffe, H. Northrop, and S.L. Stephens, 2019: Fuel dynamics and reburn severity following high-severity fire in a Sierra Nevada, USA, mixed-conifer forest. *Fire Ecology*, **15** (1), 43. https://doi.org/10.1186/s42408-019-0060-x

23. Steel, Z.L., D. Foster, M. Coppoletta, J.M. Lydersen, S.L. Stephens, A. Paudel, S.H. Markwith, K. Merriam, and B.M. Collins, 2021: Ecological resilience and vegetation transition in the face of two successive large wildfires. *Journal of Ecology*, **109** (9), 3340–3355. https://doi.org/10.1111/1365-2745.13764

24. Guiterman, C.H., R.M. Gregg, L.A.E. Marshall, J.J. Beckmann, P.J. van Mantgem, D.A. Falk, J.E. Keeley, A.C. Caprio, J.D. Coop, P.J. Fornwalt, C. Haffey, R.K. Hagmann, S.T. Jackson, A.M. Lynch, E.Q. Margolis, C. Marks, M.D. Meyer, H. Safford, A.D. Syphard, A. Taylor, C. Wilcox, D. Carril, C.A.F. Enquist, D. Huffman, J. Iniguez, N.A. Molinari, C. Restaino, and J.T. Stevens, 2022: Vegetation type conversion in the US Southwest: Frontline observations and management responses. *Fire Ecology*, **18** (1), 6. https://doi.org/10.1186/s42408-022-00131-w

25. Brooks, M.L., C.M. D'Antonio, D.M. Richardson, J.B. Grace, J.E. Keeley, J.M. DiTomaso, R.J. Hobbs, M. Pellant, and D. Pyke, 2004: Effects of invasive alien plants on fire regimes. *BioScience*, **54** (7), 677–688. https://doi.org/10.1641/0006-3568(2004)054[0677:eoiapo]2.0.co;2

26. Williamson, M.A., E. Fleishman, R.C. Mac Nally, J.C. Chambers, B.A. Bradley, D.S. Dobkin, D.I. Board, F.A. Fogarty, N. Horning, M. Leu, and M. Wohlfeil Zillig, 2020: Fire, livestock grazing, topography, and precipitation affect occurrence and prevalence of cheatgrass (*Bromus tectorum*) in the Central Great Basin, USA. *Biological Invasions*, **22** (2), 663–680. https://doi.org/10.1007/s10530-019-02120-8

27. Falk, D.A., P.J. van Mantgem, J.E. Keeley, R.M. Gregg, C.H. Guiterman, A.J. Tepley, D. Jn Young, and L.A. Marshall, 2022: Mechanisms of forest resilience. *Forest Ecology and Management*, **512**, 120129. https://doi.org/10.1016/j.foreco.2022.120129

28. Stephens, S.L., S. Thompson, G. Boisramé, B.M. Collins, L.C. Ponisio, E. Rakhmatulina, Z.L. Steel, J.T. Stevens, J.W. van Wagtendonk, and K. Wilkin, 2021: Fire, water, and biodiversity in the Sierra Nevada: A possible triple win. *Environmental Research Communications*, **3** (8), 081004. https://doi.org/10.1088/2515-7620/ac17e2

29. Kean, J.W., D.M. Staley, J.T. Lancaster, F.K. Rengers, B.J. Swanson, J.A. Coe, J.L. Hernandez, A.J. Sigman, K.E. Allstadt, and D.N. Lindsay, 2019: Inundation, flow dynamics, and damage in the 9 January 2018 Montecito debris-flow event, California, USA: Opportunities and challenges for post-wildfire risk assessment. *Geosphere*, **15** (4), 1140–1163. https://doi.org/10.1130/ges02048.1

30. Murphy, B.P., L.L. Yocom, and P. Belmont, 2018: Beyond the 1984 perspective: Narrow focus on modern wildfire trends underestimates future risks to water security. *Earth's Future*, **6** (11), 1492–1497. https://doi.org/10.1029/2018ef001006

31. Paul, M.J., S.D. LeDuc, M.G. Lassiter, L.C. Moorhead, P.D. Noyes, and S.G. Leibowitz, 2022: Wildfire induces changes in receiving waters: A review with considerations for water quality management. *Water Resources Research*, **58** (9), e2021WR030699. https://doi.org/10.1029/2021wr030699

32. Proctor, C.R., J. Lee, D. Yu, A.D. Shah, and A.J. Whelton, 2020: Wildfire caused widespread drinking water distribution network contamination. *AWWA Water Science*, **2** (4), e1183. https://doi.org/10.1002/aws2.1183

33. Aubry-Wake, C., A. Bertoncini, and J.W. Pomeroy, 2022: Fire and ice: The impact of wildfire-affected albedo and irradiance on glacier melt. *Earth's Future*, **10** (4), e2022EF002685. https://doi.org/10.1029/2022ef002685

34. Skiles, S.M.K., M. Flanner, J.M. Cook, M. Dumont, and T.H. Painter, 2018: Radiative forcing by light-absorbing particles in snow. *Nature Climate Change*, **8** (11), 964–971. https://doi.org/10.1038/s41558-018-0296-5

35. Chase, J. and P. Hansen, 2021: Displacement after the Camp Fire: Where are the most vulnerable? *Society & Natural Resources*, **34** (12), 1566–1583. https://doi.org/10.1080/08941920.2021.1977879

36. Muhs, J.W., M. Parvania, and M. Shahidehpour, 2020: Wildfire risk mitigation: A paradigm shift in power systems planning and operation. *Journal of Power and Energy*, **7**, 366–375. https://doi.org/10.1109/oajpe.2020.3030023

37. Wong-Parodi, G., 2020: When climate change adaptation becomes a "looming threat" to society: Exploring views and responses to California wildfires and public safety power shutoffs. *Energy Research & Social Science*, **70**, 101757. https://doi.org/10.1016/j.erss.2020.101757

38. Cascio, W.E., 2018: Wildland fire smoke and human health. *Science of The Total Environment*, **624**, 586–595. https://doi.org/10.1016/j.scitotenv.2017.12.086

39. Xu, R., P. Yu, M.J. Abramson, F.H. Johnston, J.M. Samet, M.L. Bell, A. Haines, K.L. Ebi, S. Li, and Y. Guo, 2020: Wildfires, global climate change, and human health. *New England Journal of Medicine*, **383**, 2173–2181. https://doi.org/10.1056/nejmsr2028985

40. Peterson, D.L., S.M. McCaffrey, and T. Patel-Weynand, Eds., 2022: *Wildland Fire Smoke in the United States: A Scientific Assessment*. Springer, Cham, Switzerland, 341 pp. https://doi.org/10.1007/978-3-030-87045-4

41. Wu, X., R.C. Nethery, M.B. Sabath, D. Braun, and F. Dominici, 2020: Air pollution and COVID-19 mortality in the United States: Strengths and limitations of an ecological regression analysis. *Science Advances*, **6** (45), 4049. https://doi.org/10.1126/sciadv.abd4049

42. Zhou, X., K. Josey, L. Kamareddine, M.C. Caine, T. Liu, L.J. Mickley, M. Cooper, and F. Dominici, 2021: Excess of COVID-19 cases and deaths due to fine particulate matter exposure during the 2020 wildfires in the United States. *Science Advances*, **7** (33), 8789. https://doi.org/10.1126/sciadv.abi8789

43. Abdo, M., I. Ward, K. O'Dell, B. Ford, J.R. Pierce, E.V. Fischer, and J.L. Crooks, 2019: Impact of wildfire smoke on adverse pregnancy outcomes in Colorado, 2007–2015. *International Journal of Environmental Research and Public Health*, **16** (19), 3720. https://doi.org/10.3390/ijerph16193720

44. Willson, B.E., N.A. Gee, N.H. Willits, L. Li, Q. Zhang, K.E. Pinkerton, and B.L. Lasley, 2021: Effects of the 2018 Camp Fire on birth outcomes in non-human primates: Case-control study. *Reproductive Toxicology*, **105**, 128–135. https://doi.org/10.1016/j.reprotox.2021.08.005

45. Méndez, M., G. Flores-Haro, and L. Zucker, 2020: The (in)visible victims of disaster: Understanding the vulnerability of undocumented Latino/a and Indigenous immigrants. *Geoforum*, **116**, 50–62. https://doi.org/10.1016/j.geoforum.2020.07.007

46. Navarro, K.M., M.T. Kleinman, C.E. Mackay, T.E. Reinhardt, J.R. Balmes, G.A. Broyles, R.D. Ottmar, L.P. Naher, and J.W. Domitrovich, 2019: Wildland firefighter smoke exposure and risk of lung cancer and cardiovascular disease mortality. *Environmental Research*, **173**, 462–468. https://doi.org/10.1016/j.envres.2019.03.060

47. Stephens, S.L., J.D. McIver, R.E. Boerner, C.J. Fettig, J.B. Fontaine, B.R. Hartsough, P.L. Kennedy, and D.W. Schwilk, 2012: The effects of forest fuel-reduction treatments in the United States. *BioScience*, **62** (6), 549–560. https://doi.org/10.1525/bio.2012.62.6.6

48. Arruda, M.R.T., T. Tenreiro, and F. Branco, 2021: Rethinking how to protect dwellings against wildfires. *Journal of Performance of Constructed Facilities*, **35** (6), 06021004. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001643

49. Knapp, E.E., Y.S. Valachovic, S.L. Quarles, and N.G. Johnson, 2021: Housing arrangement and vegetation factors associated with single-family home survival in the 2018 Camp Fire, California. *Fire Ecology*, **17** (1), 25. https://doi.org/10.1186/s42408-021-00117-0

50. Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Povak, and F.K. Lake, 2021: Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*, **31** (8), e02432. https://doi.org/10.1002/eap.2432

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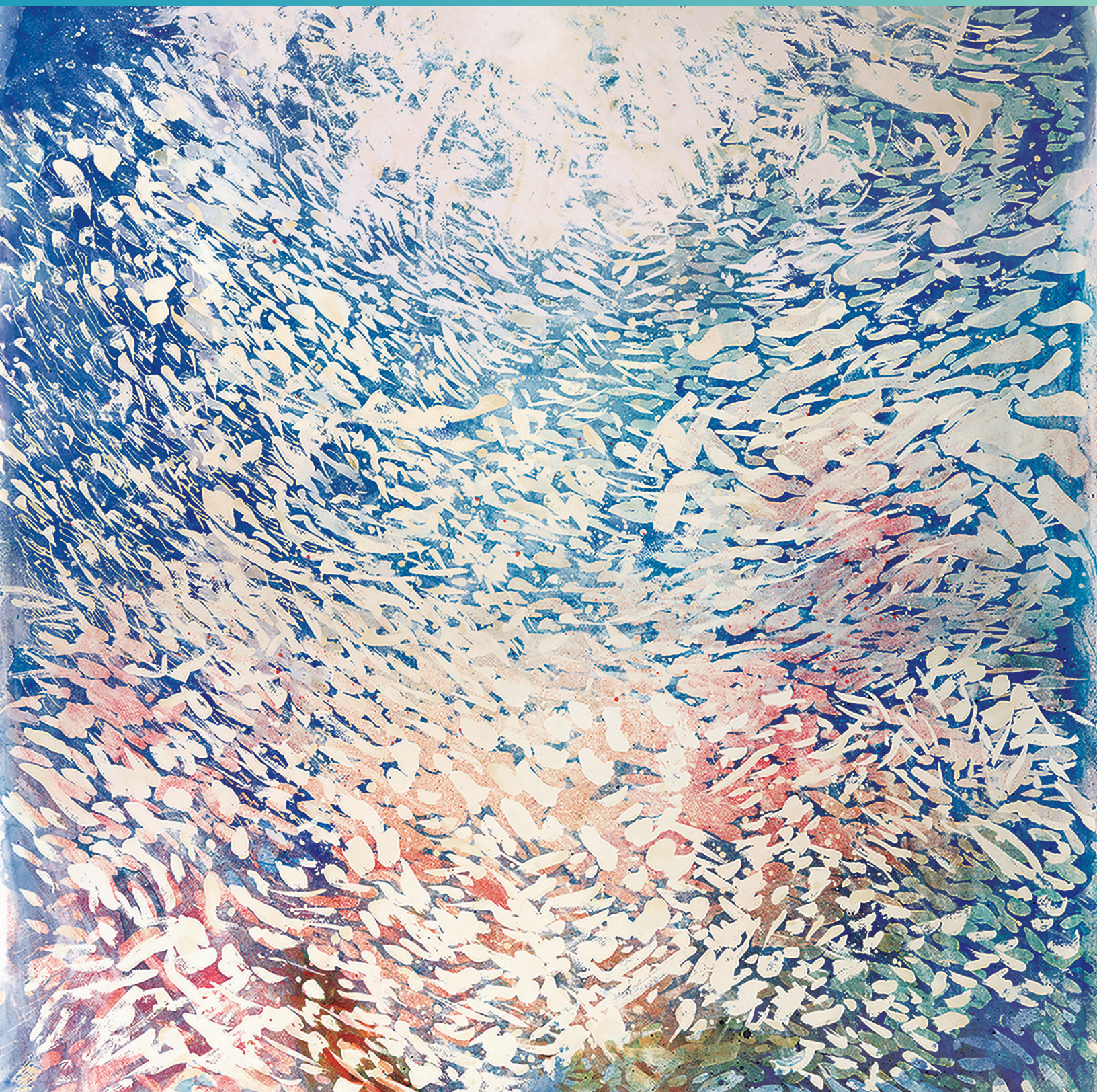

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# Focus on COVID-19 and Climate Change

Climate change can increase the likelihood of pandemics like COVID-19 and worsen their impacts. Climate-driven changes in ecosystems increase the risk of emerging infectious diseases by altering interactions among humans, pathogens, and animals and changing social and biological susceptibility to infection. Climate change also amplifies the risk of infection among people at the front lines of exposure, especially those with fewer resources. Addressing the challenges of climate change and pandemics requires early collective action and systemic change.

## *The Impact of Climate on Infectious Diseases*

Over half of known human pathogenic diseases are exacerbated by climate change,[1] particularly zoonotic (originating in animals) and vector-borne diseases (KM 15.1; Table 8.1). Zoonotic diseases account for three out of every four newly emerging pathogens, including COVID-19.[2] Changes in climate alter the distribution, diversity, and abundance of vectors and non-human hosts, as well as the host's susceptibility to pathogens and pathogen replication. Climate changes can also speed the transmission of pathogens and promote the establishment of new diseases (KMs 8.2, 15.1). Coupled with global travel networks and dense urbanization, novel pathogens can rapidly spread to areas far from their origins. Our understanding of COVID-19 is evolving, but the pandemic demonstrates the global threat of emerging infectious diseases and has raised awareness of linkages between climate change and zoonotic diseases.[3,4]

## *Interactions Between COVID-19 and Climate Change Exacerbate Existing Inequities*

Climate-related disasters have interacted with COVID-19 throughout the course of the pandemic in multiple ways (Table F3.1). Certain communities—including essential workers, older adults, low-wealth communities, and communities of color—are disproportionately impacted by these compounded exposures (KM 15.2).[5]

**Table F3.1. Interactions Between COVID-19 and Climate Change Exacerbate Existing Inequities**

The table shows examples of disproportionate impacts related to COVID-19 and climate change.

| Climate-Related Exposures | Health Impact | COVID-19 Interactions with Climate Change |
|---|---|---|
| **Hurricanes** | COVID-19 transmission | After Hurricane Laura hit the Gulf Coast in 2020, the average number of COVID-19 hospitalizations increased, compared to before the storm, and was significantly higher in counties most affected by the storm.[6] |
| **Drought** | COVID-19 transmission | Many areas, including the Colorado River basin, experienced extreme drought—a climate-related hazard—and historic reductions in water supply during the pandemic. This highlighted the lack of access to clean water for health and hygiene for more than 2 million people living in the US, the majority of whom are people of color (KM 4.2). Tribal lands without reliable access to water had higher COVID-19 incidence.[7] |
| **Wildfires, Hurricanes** | COVID-19 transmission | Crowded housing and reduced hygiene increased disease spread during disaster-related evacuations.[5,8] COVID-19 also reduced willingness to evacuate to shelters.[9] |
| **Wildfires** | COVID-19 disease severity | Wildfires exacerbate disease risk by worsening air quality (KMs 7.2, 14.2). Breathing in tiny airborne particles magnifies a person's vulnerability to COVID-19.[10,11] Smoke from the massive 2020 fires in the West was linked with increased COVID-19 cases and associated deaths.[12] |
| **Extreme Heat, Drought, Wildfires** | Livelihoods | Farmworkers—of whom approximately 70% are born outside the US—are disproportionately vulnerable to climate change impacts that exacerbate COVID-19 risk.[13,14] Extreme heat, drought, and wildfires, combined with the pandemic, negatively affected farmworker health, farm income, and the broader agricultural economy (Figure 11.1).[13,15,16] |
| **Air pollution** | COVID-19 disparities in transmission and severity | Exposure to particulate pollution can intensify COVID-19 morbidity and mortality (KM 15.2). Disparities in exposure to particulate pollution may partially explain why Indigenous, Alaska Native, Pacific Islander, Black, and Latinx Americans have experienced higher rates of COVID-19 cases, hospitalization, and death compared to White Americans.[11,17] |
| **Climate Disasters and Long-Term Threat** | Mental-health impacts | Climate change and the pandemic may significantly increase the mental health burden in the US,[18] as current inequities in access lead to widening gaps in mental health outcomes.[19,20,21] Uncertainty, frustration, hopelessness, and helplessness, coupled with loss of livelihood, drastic lifestyle changes, and disruption of routines, are linked to COVID-19 and post-COVID conditions, as well as to acute and chronic mental health impacts of climate change (KM 15.1).[22,23] |

## *Lessons from COVID-19 for Managing Climate Change*

In 2020, COVID-19 lockdowns reduced transportation and electricity generation, decreasing annual US emissions of greenhouse gases (GHGs) by 11%.[24] At the peak of COVID-19 restrictions (April 2020), emissions decreased by approximately 32%.[25,26] While emissions reductions were not sustained and had little influence on global climate,[27] they revealed the impact climate actions might have on air quality and the carbon cycle.[25,28,29,30] The short-lived decrease in GHG emissions, despite dramatic lifestyle changes, as well as public resistance to restrictions, vaccines, and masks, suggests that voluntary lifestyle changes will not be enough to achieve GHG emissions-reduction targets. Reaching net-zero emissions is achievable and would require implementing known systemic changes (KM 32.2).

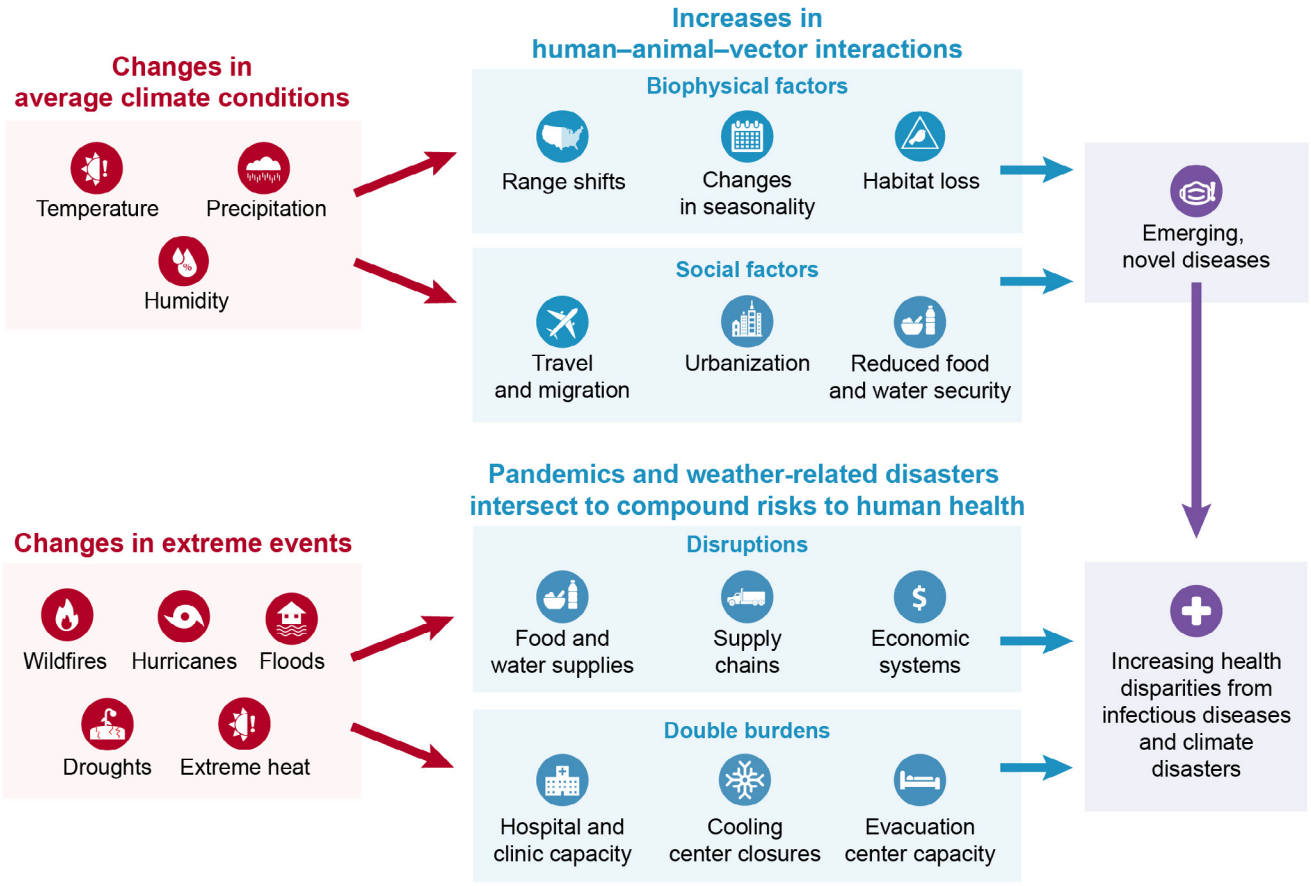
Early projections of COVID-19 costs to the US from lost economic output (i.e., income) and reduced health (i.e., premature death and long-term impairment) were calculated to be $17.9 trillion (in 2022 dollars)[31]—an underestimate given continued transmission and the high prevalence of post-COVID conditions.[32] Climate change also involves significant and inequitable direct and indirect costs, which increase with delayed response (KM 19.1). Developing solutions would help avoid significant economic costs of future pandemics and climate change.

COVID-19 and climate change have common underlying challenges and solutions.[33,34] Shared solutions include the following:

- Improved science communication that builds trust and minimizes disinformation impacts
- Collective action among nations to minimize threats
- Bottom-up and top-down programming to build community resilience
- Solutions to address stark socioeconomic, racial, and gender disparities that increase the vulnerability of those who are facing discrimination or have fewer resources
- Investments in public health and medical infrastructure that can respond to acute increases in medical burden
- Continued advancement in technology to prevent and respond to crises
- Responsive and agile systems that detect and respond to early warning signals before the worst impacts are realized

Quick action has major benefits. For COVID-19, deaths lag hospitalizations, hospitalizations lag infections, and infections lag exposures, providing time to prepare if adequate surveillance and public health systems are in place. Similarly, today's GHG emissions will affect the climate for decades to come, and delayed action has significant consequences (KM 19.1).[31] Early, preventive actions will slow or avoid the impacts of both pandemics and climate change, particularly the impacts felt by future generations. For climate change, preventive actions include achieving net-zero emissions (KM 32.1) and increasing adaptive capacity (KM 31.3). For pandemics, actions include addressing current health inequities, modernizing surveillance systems, enhancing targeted communication, mobilizing community-based prevention programs, and rapidly developing technical solutions such as vaccines. We can use the lessons learned from the COVID-19 pandemic to build resilience and to better mitigate, respond to, and recover from both the next novel pathogen and climate change.

## Climate Change and Pandemic Risks




**Climate change exacerbates infectious disease risk and increases health disparities.**

**Figure F3.1.** (**top**) Climate change is projected to alter the geographic range and seasonality of disease vectors and animal hosts due to habitat loss and changes in habitat suitability. Concurrent climate-driven changes to human social systems—such as migration and travel, growing urban centers, and food and water insecurity—increase the potential for novel pathogens to spread quickly. (**bottom**) More frequent or severe extreme weather events can simultaneously interrupt supply chains, causing further economic disruption. Extreme weather events during a pandemic can reduce healthcare capacity, increase crowding in evacuation centers, and increase exposure to extreme conditions, such as exposure to extreme heat if cooling centers are closed—all of which act together to increase health disparities. Figure credit: University of Arizona and USGCRP. See figure metadata for additional contributors.

# Traceable Accounts

## *Description of Evidence Base and Research Gaps*

The author team reviewed the current science related to COVID-19 and climate change, focusing particularly on the more measurable impacts of climate change–related disasters and their compounding impacts during the COVID-19 pandemic. There is a growing body of literature that examines the compounding health effects of COVID-19 and climate change–driven disasters and extremes.[5] Primary research articles examine the links between air pollution, wildfires, and COVID-19 susceptibility, and several case studies examine hospital capacity in areas experiencing both COVID-19 and natural disasters. These include articles that demonstrate how extreme heat during the pandemic overlapped with COVID-19 to impact vulnerable populations;[35] the COVID-19 pandemic's influence on willingness to evacuate during hurricanes;[9] the potential impact of hurricane evacuation on COVID-19 transmission;[36] and the role of wildfires on susceptibility to severe COVID-19 disease. Additional parallels between climate change and the COVID-19 pandemic have been drawn extensively within the academic literature.[5] Most of these articles are reviews of the science of these two challenges that seek to identify how they interrelate. Many of the articles raise similar themes, indicating some degree of consensus among the experts who have examined these two issues.

There remain significant gaps in understanding the role that climate change has played and will play regarding COVID-19 transmission. For example, it is unclear if, and to what extent, climate change was a driver of the emergence of the novel SARS-CoV-2 virus.[37] There is no scientific consensus and low certainty of this relationship. Questions remain about the cited increase in bat species in the region, as well as about the methods for calculating vegetation change. This illustrates the challenges in directly linking the emergence of a novel pathogen with climate change, as pathogen emergence is a downstream consequence of both first-order (i.e., geophysical changes in the climate) and second-order (shifts in forests, grasslands, and oceans) impacts of increasing GHGs. There is evidence that supports higher transmission of COVID-19 in drier and colder months, but longer time trends need to be established before there can be reliable projections of how climate change will impact transmission patterns.

For disease systems with a longer history, the role of climate change in increasing the geographic range and incidence of disease is much clearer. Zoonotic and vector-borne disease systems are particularly subject to climate change impacts. Range expansion of disease vectors is already occurring.[38,39] Changing ranges will also alter interactions among species, leading to projected increases in cross-species transmission.[40] Human movement from climate change–related disasters and loss of livelihoods are also anticipated to move pathogens around the globe[41] and expose larger numbers of individuals when these pathogens are introduced into increasingly large urban populations.[42]

# References


1. Mora, C., T. McKenzie, I.M. Gaw, J.M. Dean, H. von Hammerstein, T.A. Knudson, R.O. Setter, C.Z. Smith, K.M. Webster, J.A. Patz, and E.C. Franklin, 2022: Over half of known human pathogenic diseases can be aggravated by climate change. *Nature Climate Change*, **12** (9), 869–875. https://doi.org/10.1038/s41558-022-01426-1

2. NCEZID, 2021: Zoonotic Diseases. Centers for Disease Control and Prevention, National Center for Emerging and Zoonotic Infectious Diseases. https://www.cdc.gov/onehealth/basics/zoonotic-diseases.html

3. Gibb, R., L.H.V. Franklinos, D.W. Redding, and K.E. Jones, 2020: Ecosystem perspectives are needed to manage zoonotic risks in a changing climate. *BMJ*, **371**, m3389. https://doi.org/10.1136/bmj.m3389

4. Rodó, X., A. San-José, K. Kirchgatter, and L. López, 2021: Changing climate and the COVID-19 pandemic: More than just heads or tails. *Nature Medicine*, **27** (4), 576–579. https://doi.org/10.1038/s41591-021-01303-y

5. Phillips, C.A., A. Caldas, R. Cleetus, K.A. Dahl, J. Declet-Barreto, R. Licker, L.D. Merner, J.P. Ortiz-Partida, A.L. Phelan, E. Spanger-Siegfried, S. Talati, C.H. Trisos, and C.J. Carlson, 2020: Compound climate risks in the COVID-19 pandemic. *Nature Climate Change*, **10** (7), 586–588. https://doi.org/10.1038/s41558-020-0804-2

6. Tracey, M., A. Plemmons, and A. Belasen, 2022: Throwing caution to the wind: How hurricanes affect COVID-19 spread. *Health Economics*, **31** (6), 1258–1265. https://doi.org/10.1002/hec.4499

7. Rodriguez-Lonebear, D., N.E. Barceló, R. Akee, and S.R. Carroll, 2020: American Indian reservations and COVID-19: Correlates of early infection rates in the pandemic. *Journal of Public Health Management and Practice*, **26** (4), 371–377. https://doi.org/10.1097/phh.0000000000001206

8. Shultz, J.M., C. Fugate, and S. Galea, 2020: Cascading risks of COVID-19 resurgence during an active 2020 Atlantic hurricane season. JAMA, **324** (10), 935–936. https://doi.org/10.1001/jama.2020.15398

9. Collins, J., A. Polen, K. McSweeney, D. Colón-Burgos, and I. Jernigan, 2021: Hurricane risk perceptions and evacuation decision-making in the age of COVID-19. *Bulletin of the American Meteorological Society*, **102** (4), E836–E848. https://doi.org/10.1175/bams-d-20-0229.1

10. Pozzer, A., F. Dominici, A. Haines, C. Witt, T. Münzel, and J. Lelieveld, 2020: Regional and global contributions of air pollution to risk of death from COVID-19. *Cardiovascular Research*, **116** (14), 2247–2253. https://doi.org/10.1093/cvr/cvaa288

11. Wu, X., R.C. Nethery, M.B. Sabath, D. Braun, and F. Dominici, 2020: Air pollution and COVID-19 mortality in the United States: Strengths and limitations of an ecological regression analysis. *Science Advances*, **6** (45), 4049. https://doi.org/10.1126/sciadv.abd4049

12. Zhou, X., K. Josey, L. Kamareddine, M.C. Caine, T. Liu, L.J. Mickley, M. Cooper, and F. Dominici, 2021: Excess of COVID-19 cases and deaths due to fine particulate matter exposure during the 2020 wildfires in the United States. *Science Advances*, **7** (33), 8789. https://doi.org/10.1126/sciadv.abi8789

13. Castillo, F., A.M. Mora, G.L. Kayser, J. Vanos, C. Hyland, A.R. Yang, and B. Eskenazi, 2021: Environmental health threats to Latino migrant farmworkers. *Annual Review of Public Health*, **42** (1), 257–276. https://doi.org/10.1146/annurev-publhealth-012420-105014

14. DOL, 2022: Findings from the National Agricultural Workers Survey (NAWS) 2019–2020: A Demographic and Employment Profile of United States Farmworkers. Research Report No. 16. U.S. Department of Labor. https://www.dol.gov/sites/dolgov/files/eta/naws/pdfs/naws%20research%20report%2016.pdf

15. Croptracker, 2022: Adaptation salvaged a scorching hot cherry harvest. Where does recurring, dangerous heat leave farm labor – and the apples that are up next? *Croptracker*. https://www.croptracker.com/blog/cherry-harvest-retrospective.html

16. Lassalle, L., 2020: Local ranchers face backlog of cattle due to coronavirus. Now comes the drought. *The Aspen Times*, September 7, 2020. https://www.aspentimes.com/news/local-ranchers-face-backlog-of-cattle-due-to-coronavirus-now-comes-the-drought/

17. NCIRD, 2022: Risk for COVID-19 Infection, Hospitalization, and Death By Race/Ethnicity. Centers for Disease Control and Prevention, National Center for Immunization and Respiratory Diseases. https://stacks.cdc.gov/view/cdc/105453

18. Fisher, A., A. Roberts, A.R. McKinlay, D. Fancourt, and A. Burton, 2021: The impact of the COVID-19 pandemic on mental health and well-being of people living with a long-term physical health condition: A qualitative study. *BMC Public Health*, **21** (1), 1801. https://doi.org/10.1186/s12889-021-11751-3

19. Chen, A.K., X. Wang, L.P. McCluskey, J.C. Morgan, J.A. Switzer, R. Mehta, M. Tingen, S. Su, R.A. Harris, D.C. Hess, and E.K. Rutkowski, 2022: Neuropsychiatric sequelae of long COVID-19: Pilot results from the COVID-19 neurological and molecular prospective cohort study in Georgia, USA. *Brain, Behavior, & Immunity - Health*, **24**, 100491. https://doi.org/10.1016/j.bbih.2022.100491

20. Pfefferbaum, B. and C.S. North, 2020: Mental health and the COVID-19 pandemic. *New England Journal of Medicine*, **383** (6), 510–512. https://doi.org/10.1056/nejmp2008017

21. Titze-de-Almeida, R., T.R. da Cunha, L.D. Dos Santos Silva, C.S. Ferreira, C.P. Silva, A.P. Ribeiro, A. de Castro Moreira Santos Júnior, P.R. de Paula Brandão, A.P.B. Silva, M.C.O. da Rocha, M.-A.E. Xavier, S.S. Titze-de-Almeida, H.E. Shimizu, and R.N. Delgado-Rodrigues, 2022: Persistent, new-onset symptoms and mental health complaints in Long COVID in a Brazilian cohort of non-hospitalized patients. *BMC Infectious Diseases*, **22** (1), 1–11. https://doi.org/10.1186/s12879-022-07065-3

22. Hoppe, B.O., L. Prussia, C. Manning, K.K. Raab, and K.V. Jones-Casey, 2023: "It's hard to give hope sometimes": Climate change, mental health, and the challenges for mental health professionals. *Ecopsychology*, **15** (1), 13–25. https://doi.org/10.1089/eco.2022.0032

23. Marazziti, D., P. Cianconi, F. Mucci, L. Foresi, I. Chiarantini, and A. Della Vecchia, 2021: Climate change, environment pollution, COVID-19 pandemic and mental health. *Science of The Total Environment*, **773**, 145182. https://doi.org/10.1016/j.scitotenv.2021.145182

24. EPA, 2022: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020. EPA 430-R-22-003. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020

25. Friedlingstein, P., M.W. Jones, M. O'Sullivan, R.M. Andrew, D.C.E. Bakker, J. Hauck, C. Le Quéré, G.P. Peters, W. Peters, J. Pongratz, S. Sitch, J.G. Canadell, P. Ciais, R.B. Jackson, S.R. Alin, P. Anthoni, N.R. Bates, M. Becker, N. Bellouin, L. Bopp, T.T.T. Chau, F. Chevallier, L.P. Chini, M. Cronin, K.I. Currie, B. Decharme, L.M. Djeutchouang, X. Dou, W. Evans, R.A. Feely, L. Feng, T. Gasser, D. Gilfillan, T. Gkritzalis, G. Grassi, L. Gregor, N. Gruber, Ö. Gürses, I. Harris, R.A. Houghton, G.C. Hurt, Y. Iida, T. Ilyina, I.T. Luijkx, A. Jain, S.D. Jones, E. Kato, D. Kennedy, K. Klein Goldewijk, J. Knauer, J.I. Korsbakken, A. Körtzinger, P. Landschützer, S.K. Lauvset, N. Lefèvre, S. Lienert, J. Liu, G. Marland, P.C. McGuire, J.R. Melton, D.R. Munro, J.E.M.S. Nabel, S.I. Nakaoka, Y. Niwa, T. Ono, D. Pierrot, B. Poulter, G. Rehder, L. Resplandy, E. Robertson, C. Rödenbeck, T.M. Rosan, J. Schwinger, C. Schwingshackl, R. Séférian, A.J. Sutton, C. Sweeney, T. Tanhua, P.P. Tans, H. Tian, B. Tilbrook, F. Tubiello, G.R. van der Werf, N. Vuichard, C. Wada, R. Wanninkhof, A.J. Watson, D. Willis, A.J. Wiltshire, W. Yuan, C. Yue, X. Yue, S. Zaehle, and J. Zeng, 2022: Global carbon budget 2021. *Earth System Science Data*, **14** (4), 1917–2005. https://doi.org/10.5194/essd-14-1917-2022

26. Le Quéré, C., R.B. Jackson, M.W. Jones, A.J.P. Smith, S. Abernethy, R.M. Andrew, A.J. De-Gol, D.R. Willis, Y. Shan, J.G. Canadell, P. Friedlingstein, F. Creutzig, and G.P. Peters, 2020: Temporary reduction in daily global $CO_2$ emissions during the COVID-19 forced confinement. *Nature Climate Change*, **10** (7), 647–653. https://doi.org/10.1038/s41558-020-0797-x

27. Jackson, R.B., P. Friedlingstein, C. Le Quéré, S. Abernethy, R.M. Andrew, J.G. Canadell, P. Ciais, S.J. Davis, Z. Deng, Z. Liu, J.I. Korsbakken, and G.P. Peters, 2022: Global fossil carbon emissions rebound near pre-COVID-19 levels. *Environmental Research Letters*, **17** (3), 031001. https://doi.org/10.1088/1748-9326/ac55b6

28. Gettelman, A., R. Lamboll, C.G. Bardeen, P.M. Forster, and D. Watson-Parris, 2021: Climate impacts of COVID-19 induced emission changes. *Geophysical Research Letters*, **48** (3), e2020GL091805. https://doi.org/10.1029/2020gl091805

29. Laughner, J.L., J.L. Neu, D. Schimel, P.O. Wennberg, K. Barsanti, K.W. Bowman, A. Chatterjee, B.E. Croes, H.L. Fitzmaurice, D.K. Henze, J. Kim, E.A. Kort, Z. Liu, K. Miyazaki, A.J. Turner, S. Anenberg, J. Avise, H. Cao, D. Crisp, J.d. Gouw, A. Eldering, J.C. Fyfe, D.L. Goldberg, K.R. Gurney, S. Hasheminassab, F. Hopkins, C.E. Ivey, D.B.A. Jones, J. Liu, N.S. Lovenduski, R.V. Martin, G.A. McKinley, L. Ott, B. Poulter, M. Ru, S.P. Sander, N. Swart, Y.L. Yung, and Z.-C. Zeng, 2021: Societal shifts due to COVID-19 reveal large-scale complexities and feedbacks between atmospheric chemistry and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (46), e2109481118. https://doi.org/10.1073/pnas.2109481118

30. Lovenduski, N.S., A. Chatterjee, N.C. Swart, J.C. Fyfe, R.F. Keeling, and D. Schimel, 2021: On the detection of COVID-driven changes in atmospheric carbon dioxide. *Geophysical Research Letters*, **48** (22), e2021GL095396. https://doi.org/10.1029/2021gl095396

31. Cutler, D.M. and L.H. Summers, 2020: The COVID-19 pandemic and the $16 trillion virus. JAMA, **324** (15), 1495–1496. https://doi.org/10.1001/jama.2020.19759

32. Cutler, D.M., 2022: The costs of long Covid. *JAMA Health Forum*, **3** (5), e221809. https://doi.org/10.1001/jamahealthforum.2022.1809

33. Klenert, D., F. Funke, L. Mattauch, and B. O'Callaghan, 2020: Five lessons from COVID-19 for advancing climate change mitigation. *Environmental and Resource Economics*, **76** (4), 751–778. https://doi.org/10.1007/s10640-020-00453-w

34. Manzanedo, R.D. and P. Manning, 2020: COVID-19: Lessons for the climate change emergency. *Science of The Total Environment*, **742**, 140563. https://doi.org/10.1016/j.scitotenv.2020.140563

35. Wilhelmi, O.V., P.D. Howe, M.H. Hayden, and C.R. O'Lenick, 2021: Compounding hazards and intersecting vulnerabilities: Experiences and responses to extreme heat during COVID-19. *Environmental Research Letters*, **16** (8), 084060. https://doi.org/10.1088/1748-9326/ac1760

36. Pei, S., K.A. Dahl, T.K. Yamana, R. Licker, and J. Shaman, 2020: Compound risks of hurricane evacuation amid the COVID-19 pandemic in the United States. *GeoHealth*, **4** (12), e2020GH000319. https://doi.org/10.1029/2020gh000319

37. Beyer, R.M., A. Manica, and C. Mora, 2021: Shifts in global bat diversity suggest a possible role of climate change in the emergence of SARS-CoV-1 and SARS-CoV-2. *Science of The Total Environment*, **767**, 145413. https://doi.org/10.1016/j.scitotenv.2021.145413

38. Gilbert, L., 2021: The impacts of climate change on ticks and tick-borne disease risk. *Annual Review of Entomology*, **66** (1), 373–388. https://doi.org/10.1146/annurev-ento-052720-094533

39. Rocklöv, J. and R. Dubrow, 2020: Climate change: An enduring challenge for vector-borne disease prevention and control. *Nature Immunology*, **21** (5), 479–483. https://doi.org/10.1038/s41590-020-0648-y

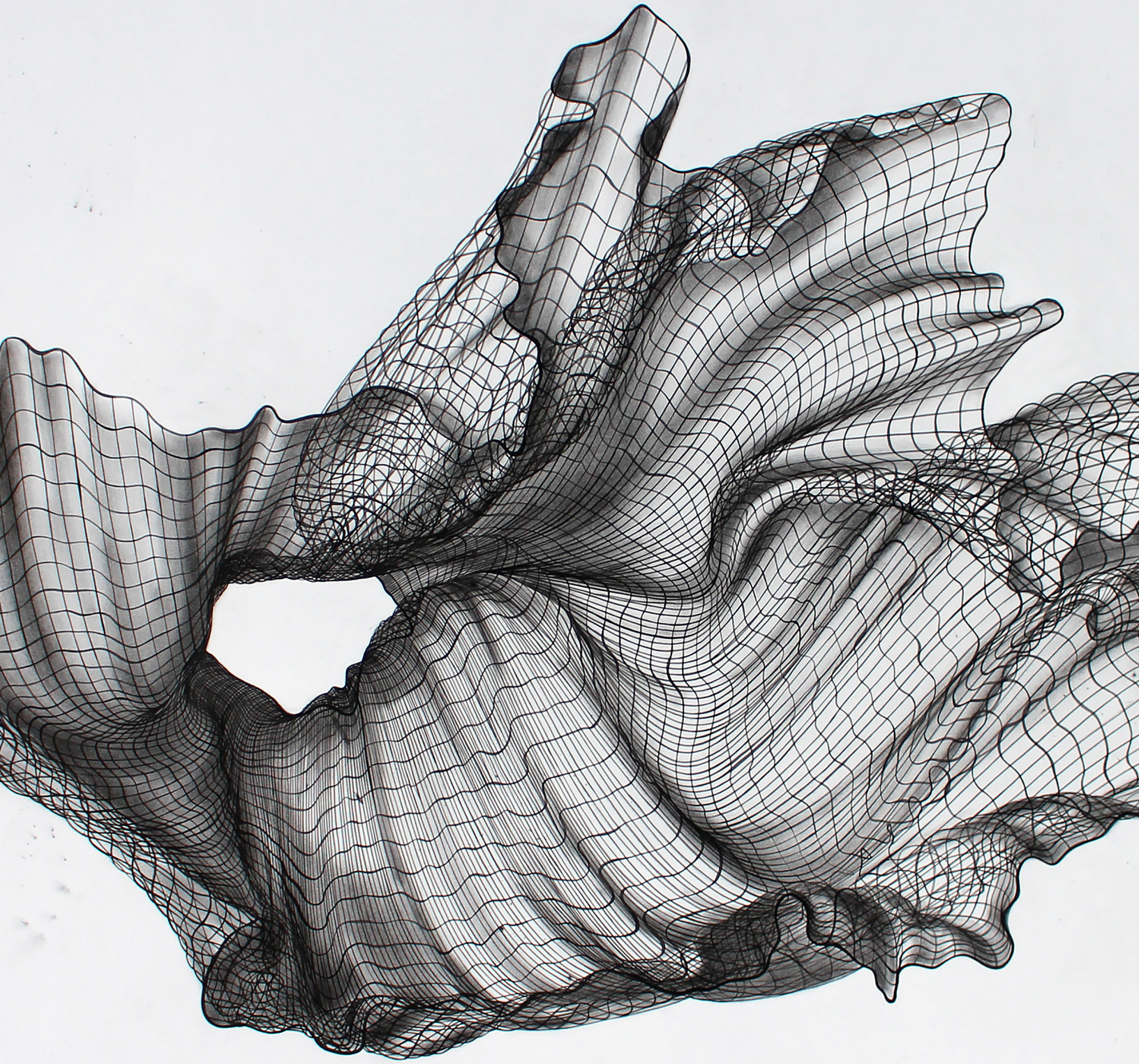
40. Carlson, C.J., G.F. Albery, C. Merow, C.H. Trisos, C.M. Zipfel, E.A. Eskew, K.J. Olival, N. Ross, and S. Bansal, 2022: Climate change increases cross-species viral transmission risk. *Nature*, **607** (7919), 555–562. https://doi.org/10.1038/s41586-022-04788-w

41. Semenza, J.C. and K.L. Ebi, 2019: Climate change impact on migration, travel, travel destinations and the tourism industry. *Journal of Travel Medicine*, **26** (5), taz026. https://doi.org/10.1093/jtm/taz026

42. Combs, M.A., P.A. Kache, M.C. VanAcker, N. Gregory, L.D. Plimpton, D.M. Tufts, M.P. Fernandez, and M.A. Diuk-Wasser, 2022: Socio-ecological drivers of multiple zoonotic hazards in highly urbanized cities. *Global Change Biology*, **28** (5), 1705–1724. https://doi.org/10.1111/gcb.16033

Fifth National Climate Assessment

# Focus on Risks to Supply Chains



# Focus on Risks to Supply Chains

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# Focus on Risks to Supply Chains

Damage to supply chain networks caused by climate change reverberates through people's livelihoods and investments in ways that threaten quality of life and security, often in lasting and inequitable ways. Coordinated efforts can mediate impacts and help communities and companies adapt to these large, interconnected, and recurring risks. However, the pace, scale, and scope of efforts that have been undertaken to transform supply chains are not yet sufficient to meet either current or expected disruptions and costs.

A supply chain represents the entire flow of goods and services, from the sourcing of raw materials to the delivery of a product or service to the customer. Supply chains operate globally across complex and interdependent networks of infrastructure, activities, and resources and include producers, manufacturers, and distributors. Upstream portions of supply chains encompass the range of activities needed to produce the product or service, while downstream portions encompass the range of activities needed to get the product or service to its final consumer. Supply chain management predominantly follows a linear model (take, make, and dispose), but a circular model is emerging that addresses sustainability by adding elements of recycling or refurbishing products.[1] Supply chains depend on the physical transportation of goods and services, as well as on digital networks to provide logistical support, to track movement of goods and services or other important information (e.g., immutable ledgers on investment and financial transactions on blockchain networks), and to deliver goods and services (e.g., telemedicine or remote education). In addition to physical and digital infrastructure, supply chains depend on networks of people to manage and service them.

Climate-driven disruptions to supply chains cascade and compound across multiple systems, underlining the need to understand and manage climate-related risks (KMs 17.1, 18.1, 19.2). These compounding risks include deepening of existing inequities in risk distribution and resource access for overburdened communities (KMs 16.1, 20.1),[2] geopolitical instability and national security vulnerabilities (KM 17.2),[3] and the inability to achieve emissions reductions due to the lack of capacity and provisioning for the electrification of products and services (KMs 5.2, 13.4, 17.3). Climate change also has complex interactions with non-climate global shocks such as the COVID-19 pandemic (see Focus on COVID-19 and Climate Change). Current supply chain vulnerabilities show the need to adapt to avoid future interruptions (KMs 7.1, 11.2, 15.3, 20.2, 31.3).[4,5] Climate-related risks to supply chains threaten the livelihoods of suppliers, distributors, and laborers, as well as infrastructure (KMs 7.2, 21.2, 22.1). In 2021, builders paid more for materials due to West Coast wildfires and an active US housing market.[6] Extreme heat and flooding at ports and transportation hubs has impacted goods movement.[7] Overlooking these risks prolongs economic consequences to suppliers and customers, prompting fundamental shifts in global supply chains, consumption patterns, and competition over constrained natural resources (KMs 8.3, 10.1, 18.1, 19.3, 20.1, 30.1).[8]

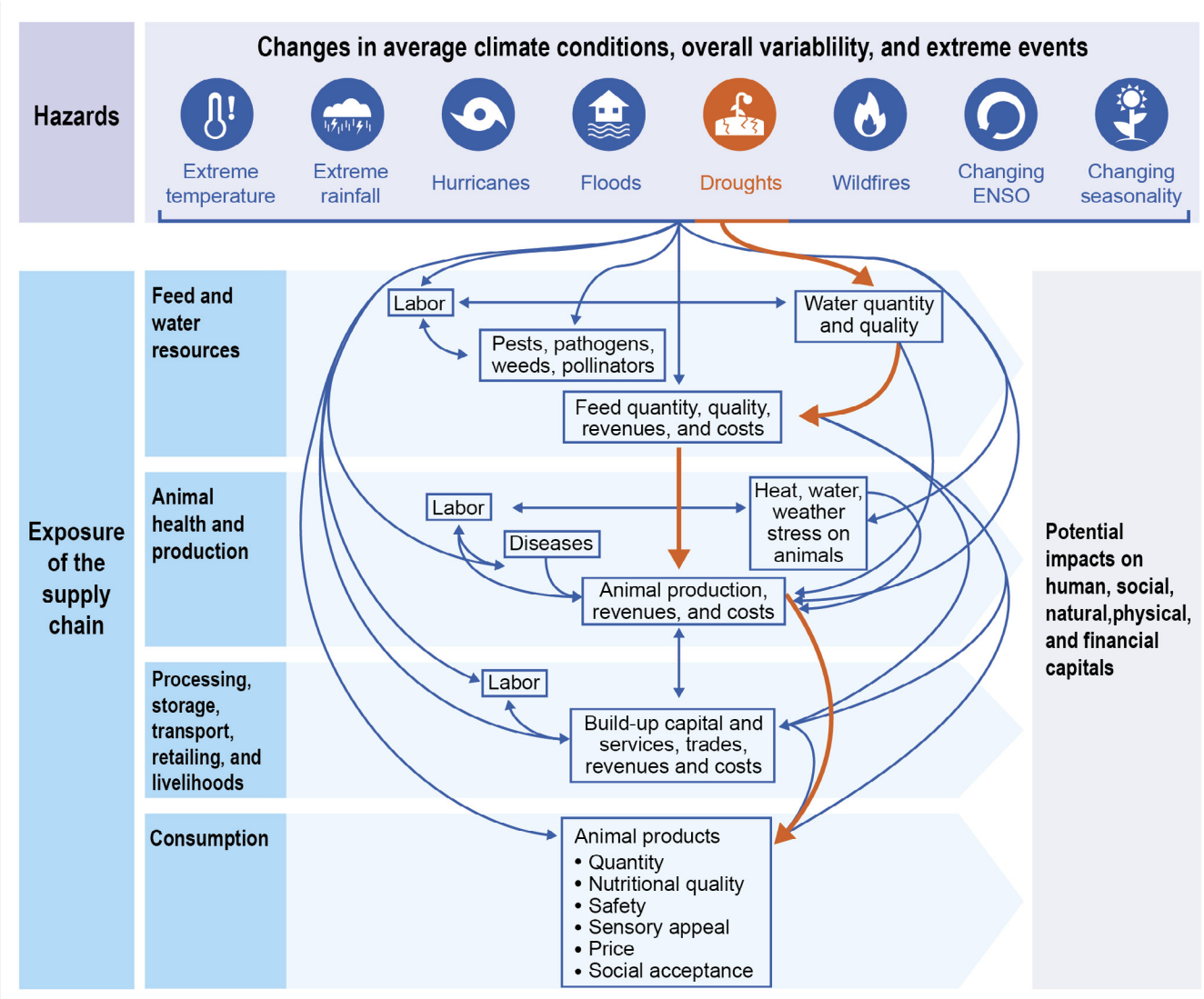
As an example, each stage in the food supply chain, including production, storage, processing, distribution, retail, and household food security, is vulnerable to climate change—from gradual changes in average climate conditions (e.g., precipitation and temperature) to increases in the frequency and intensity of extreme events (e.g., floods, drought, wildfire) and smoke migration (Figure F4.1; KMs 9.1, 10.3, 3.2, 14.2, 28.5, 29.3).[9] Sudden shocks to the food supply chain can have local to global impacts on food security, justice, and human migration patterns (KMs 11.2, 28.3, 29.3).[10,11] Extreme events in other countries raise domestic food prices and limit availability due to global supply chain interdependencies (KMs 6.1, 17.1, 9.1).

The transition to low-carbon energy sources to mitigate future climate change is accelerating demand for the upstream minerals, bulk electric supply goods (e.g., transformers, parts, chemicals), and materials for energy infrastructure and technologies.[12,13,14] Global competition, geopolitical tensions, and supply chain disruptions, along with a national lack of trained workers and inflation-related constraints on investment capital, are shifting materials sourcing (KMs 18.1, 21.5).[15] These disruptions will continue to hinder the global supply chains underpinning development and deployment of technologies for low-carbon and renewable energy generation and supply, as well as the related technologies for emissions mitigation, carbon capture, and electrification critical to achieving net-zero emissions (KM 32.1). Strategies are emerging to secure these critical energy development supplies. These include shifting to upstream sourcing from lower-risk countries near manufacturing sites, assisting countries to bolster mining and refining capacity, building redundant supply chains, and developing alternative materials or processes (Figure 17.2).[3] However, meeting the demand for these inputs may disproportionately harm overburdened and Indigenous communities, fueling inequality, political unrest, and economic loss in US-based investment and interests (KMs 5.2, 16.2, 18.2, 17.3).

Climate adaptation and emissions mitigation will require major transformations of supply chain transportation infrastructure and technologies (Chs. 31, 32).[16] The COVID-19 pandemic showed the sharp demand fluctuations, fragility, and chokepoints of an evolving, multimodal transportation system.[17] This system underlies the supply chain yet increases environmental injustices by siting warehouses and freight ways in overburdened communities (KMs 12.2, 13.4, 15.1, 29.2).[18] Adaptations in digitalization and related technologies (including e-commerce, electric-drive or automated vehicles, and related infrastructure), along with insufficiently localized supply chains, long-standing workforce challenges, and cybersecurity risks, all place demands on and pose risks to supply chain transportation systems. These challenges increase the importance of multisectoral and equity-centered planning and action for transportation (KMs 5.2, 13.2).

Integrated global supply chains will continue to be threatened by climate change and will in turn influence how the Nation responds to climate change. Markets often respond quickly if there are alternate materials or inputs available that are economically viable. Such shifts can present opportunities for disclosure of material risks, informed investment and improved livelihoods in local job creation, domestic economic activity, and innovation across sectors and technologies.[19,20] To protect the quality and security of life for all would require a rapid acceleration of supply chain adaptation measures that increase flexibility and ensure equitable access to goods and services.

## Climate Change and Food Supply




**Climate change poses challenges to the animal food products supply chain.**

**Figure F4.1.** The figure shows potential climate change vulnerabilities of the livestock food supply chain, including impacts on feed and water resources; animal health and production; processing, storage, transport, retailing, and livelihoods; and human consumption. Blue lines indicate how climate change hazards can impact various sectors of the supply chain either directly or through cascading effects. Highlighted in orange is an example of the cascading effects of drought, where reduced water quantity decreases animal feed quantity, which in turn reduces animal production, resulting in increased food prices for consumers and an increased demand for deforestation-free agriculture and forest products. ENSO refers to El Niño–Southern Oscillation. Adapted from Godde et al. 2021[21] [CC BY 4.0].

# Traceable Accounts

## *Description of Evidence Base and Research Gaps*

Extensive evidence and recent lived experience during the ongoing pandemic confirm how supply chains are a core factor in the quality of life and national security of the United States.[5] Multiple examples from across this Assessment show that climate change burdens supply chains and challenges effective, efficient, and equitable provisioning of goods and services. These challenges play out differently depending on a supply chain's sourcing, distribution networks, and many complex factors that are beyond the scope of this discussion.[15] Supply chain climate vulnerabilities are distributed unevenly both globally and within the United States and are known but not well quantified. This uncertainty reflects disparities in the access to materials, technologies, and infrastructure (both physical and digital) that influence decision-making in supply chain management.

It is difficult to predict the expected changes of climate risks on supply chains, as well as human responses due to shocks and stressors. This uncertainty is due in part to the many complex factors that influence the size and composition of supply chains. The degree to which climate change will exacerbate challenges to existing supply chains also depends on the future frequency and intensity of extreme weather events. Finally, there is uncertainty in the choices that businesses and governments make in terms of policy to address risks, build resilience into supply chains, and ensure equitable distribution.[20]

Supply chains enable production of low-emitting energy technologies but are also sources of emissions themselves. Tracking emissions from activities across supply chains is of growing importance both to companies and to investors and disclosure organizations. Discussion of this topic is beyond the scope of this discussion.

# References


1. Farooque, M., A. Zhang, M. Thürer, T. Qu, and D. Huisingh, 2019: Circular supply chain management: A definition and structured literature review. *Journal of Cleaner Production*, **228**, 882–900. https://doi.org/10.1016/j.jclepro.2019.04.303

2. Jin, H. and Y. Lu, 2021: SAR-Gi*: Taking a spatial approach to understand food deserts and food swamps. *Applied Geography*, **134**, 102529. https://doi.org/10.1016/j.apgeog.2021.102529

3. DOD, 2022: Securing Defense-Critical Supply Chains: An Action Plan Developed in Response to President Biden's Executive Order 14017. U.S. Department of Defense. https://media.defense.gov/2022/feb/24/2002944158/-1/-1/1/dod-eo-14017-report-securing-defense-critical-supply-chains.pdf

4. Le Page, M., 2022: China's worst heatwave. *New Scientist*, **255** (3401), 7. https://doi.org/10.1016/s0262-4079(22)01506-8

5. Melnyk, S.A., T. Schoenherr, V. Verter, C. Evans, and C. Shanley, 2021: The pandemic and SME supply chains: Learning from early experiences of SME suppliers in the U.S. defense industry. *Journal of Purchasing and Supply Management*, **27** (4), 100714. https://doi.org/10.1016/j.pursup.2021.100714

6. Graffeo, E., 2021: Lumber prices spike as wildfires cause producers to cut output, citing 'significant' supply chain challenges. *Markets Insider*, July 22, 2021. https://markets.businessinsider.com/news/commodities/lumber-prices-canfor-wildfires-production-cut-futures-commodity-supply-chain-2021-7

7. Izaguirre, C., I.J. Losada, P. Camus, J.L. Vigh, and V. Stenek, 2021: Climate change risk to global port operations. *Nature Climate Change*, **11** (1), 14–20. https://doi.org/10.1038/s41558-020-00937-z

8. Wang, D., D. Guan, S. Zhu, M.M. Kinnon, G. Geng, Q. Zhang, H. Zheng, T. Lei, S. Shao, P. Gong, and S.J. Davis, 2021: Economic footprint of California wildfires in 2018. *Nature Sustainability*, **4** (3), 252–260. https://doi.org/10.1038/s41893-020-00646-7

9. Coleman-Jensen, A., M.P. Rabbitt, C.A. Gregory, and A. Singh, 2021: Household Food Security in the United States in 2020. ERR-298. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=102075

10. Bermeo, S., D. Leblang, and G.N. Alverio, 2022: Root Causes of Migration from Guatemala: Analysis of Subnational Trends. Duke University Sanford School of Public Policy, Center for International Development, 8 pp. https://sanford-dcid-files.cloud.duke.edu/sites/default/files/Migration-Policy-Brief-Guatemala.pdf

11. Thomas, K.A. and B.P. Warner, 2019: Weaponizing vulnerability to climate change. *Global Environmental Change*, **57**, 101928. https://doi.org/10.1016/j.gloenvcha.2019.101928

12. EPRI, 2022: Understanding Generation and Storage Technology Supply Chain Risks and Needs to Support Electric Utility Sector Decarbonization. Electric Power Research Institute, 36 pp. https://www.epri.com/research/products/000000003002023228

13. Moser, S. and J.F. Hart, 2018: The Adaptation Blindspot: Teleconnected and Cascading Impacts of Climate Change in the Electrical Grid and Lifelines of Los Angeles. Publication Number: CCCA4-CEC-2018-008. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-11/energy_ccca4-cec-2018-008_ada.pdf

14. Moser, S.C. and J.A.F. Hart, 2015: The long arm of climate change: Societal teleconnections and the future of climate change impacts studies. *Climatic Change*, **129** (1), 13–26. https://doi.org/10.1007/s10584-015-1328-z

15. McNulty, B.A. and S.M. Jowitt, 2021: Barriers to and uncertainties in understanding and quantifying global critical mineral and element supply. *iScience*, **24** (7), 102809. https://doi.org/10.1016/j.isci.2021.102809

16. Tamor, M.A. and E.B. Stechel, 2022: Electrification of transportation means a lot more than a lot more electric vehicles. *iScience*, **25** (6), 104376. https://doi.org/10.1016/j.isci.2022.104376

17. Schofer, J.L., H.S. Mahmassani, and M.T.M. Ng, 2022: Resilience of U.S. rail intermodal freight during the COVID-19 pandemic. *Research in Transportation Business & Management*, **43**, 100791. https://doi.org/10.1016/j.rtbm.2022.100791

18. Yuan, Q., 2019: Does context matter in environmental justice patterns? Evidence on warehousing location from four metro areas in California. *Land Use Policy*, **82**, 328–338. https://doi.org/10.1016/j.landusepol.2018.12.011

19. FSOC, 2021: Report on Climate-Related Financial Risk. Financial Stability Oversight Council, Washington, DC. https://home.treasury.gov/system/files/261/FSOC-Climate-Report.pdf

20. SEC, 2022: The Enhancement and Standardization of Climate-Related Disclosures for Investors. Securities and Exchange Commission, 490 pp. https://www.sec.gov/rules/proposed/2022/33-11042.pdf

21. Godde, C.M., D. Mason-D'Croz, D.E. Mayberry, P.K. Thornton, and M. Herrero, 2021: Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, **28**, 100488. https://doi.org/10.1016/j.gfs.2020.100488

Fifth National Climate Assessment

# Focus on Blue Carbon

# Focus on Blue Carbon

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# Focus on Blue Carbon

Blue carbon refers to carbon captured by marine and coastal ecosystems, such as mangroves, coastal wetlands, and seagrasses. Coastal ecosystems sequester carbon at a much faster rate than terrestrial ecosystems, and the carbon stored belowground can remain in place for decades to millennia if undisturbed by humans or extreme events. Conservation and restoration of coastal ecosystems can play a role in reducing carbon dioxide accumulations in the atmosphere by increasing sequestration of blue carbon.

## *Why So Blue, Carbon?*

Blue carbon is the marine analog of green carbon, which refers to carbon captured by terrestrial (i.e., land-based) plants.[1] Marine ecosystems are aquatic environments with high salinity levels, including the open ocean, deep sea ocean, and coastal ecosystems. Marine and terrestrial plants capture and store carbon through photosynthesis and the accumulation of organic matter, such as roots, in the soil.[1,2] Blue carbon ecosystems (BCEs) are coastal ecosystems such as mangroves, wetlands, and seagrasses that store most of their carbon belowground in ocean sediments. Acre for acre, BCEs are estimated to store about twice as much carbon belowground than terrestrial vegetation (Figure F5.1).[3,4]

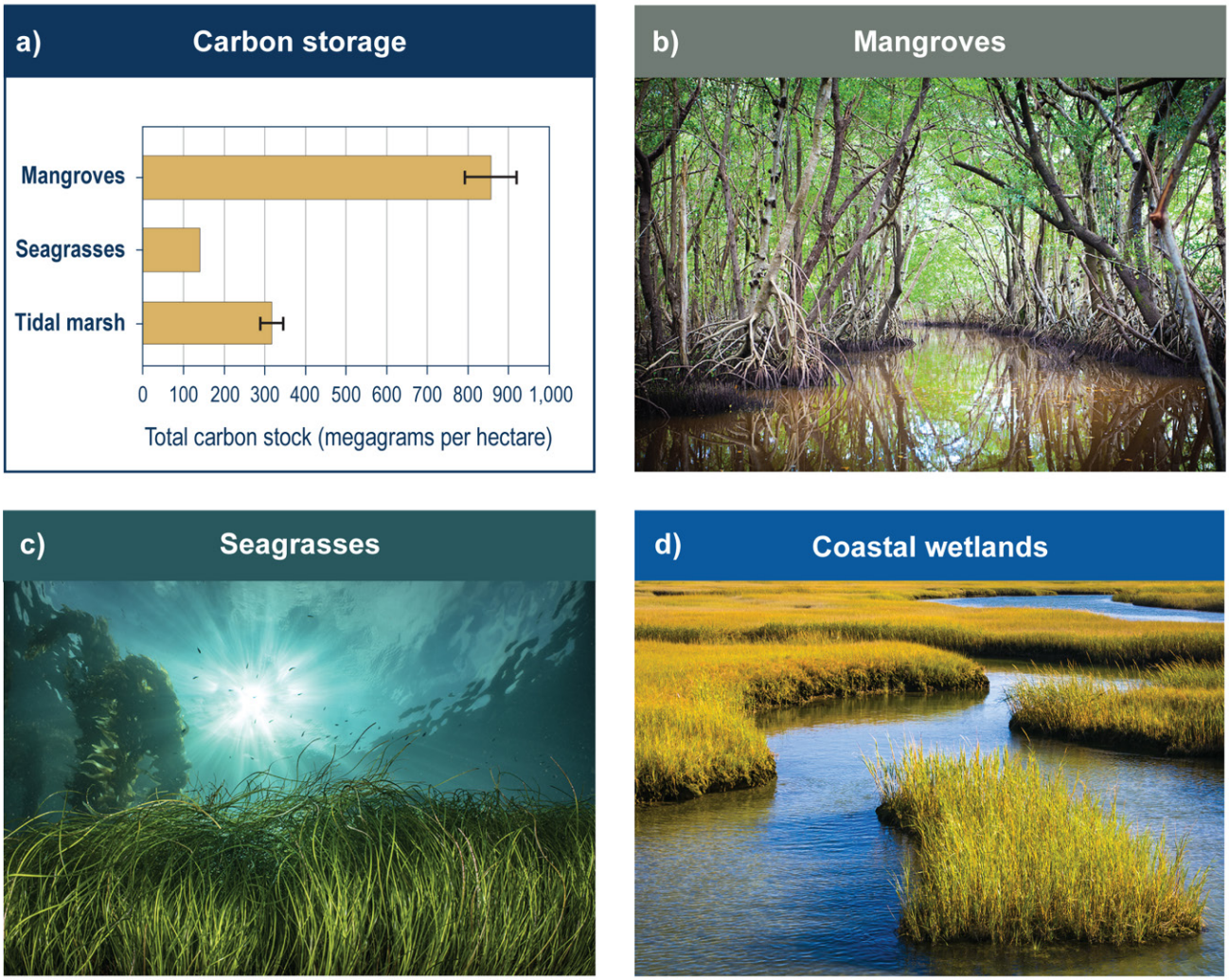
## *The Carbon Benefits*

BCEs' ability to capture and store carbon has spawned numerous international efforts that support blue carbon as a natural climate mitigation option through enhanced stewardship, management, conservation, and restoration of these ecosystems and the ecosystem services and co-benefits they provide (KM 8.3).[2,3,5] This work includes creating and improving financing and policy mechanisms for coastal restoration that increases carbon sequestration,[6,7,8] as well as developing methods to better quantify carbon sequestration.[9,10,11]

The importance of estimating carbon emissions and sequestration in BCEs is recognized in international policies such as the Intergovernmental Panel on Climate Change (IPCC) guidelines for greenhouse gas inventories.[12] The United States has included coastal wetlands within its annual national inventory of greenhouse gas emissions and sinks,[13,14] and the government monitors sites across the US with the most blue carbon storage potential, such as the Florida Everglades, San Francisco Bay, and Chesapeake Bay. Globally, the US has one of the highest rates of BCE losses, largely due to hurricanes and coastal erosion.[15]

With conservation and restoration, BCEs could sequester enough carbon each year to offset about 3 percent of global emissions (based on 2019 and 2020 emissions).[3] Other coastal and marine ecosystems or species, such as kelp forests, freshwater wetlands, phytoplankton, and the deep sea may also capture carbon; however, the carbon sequestration potential of these ecosystems and species is likely lower than BCEs (Figure 8.19).[16,17]

## Blue Carbon Ecosystem Sequestration Potential




**Coastal blue carbon ecosystems play an important role in carbon sequestration but are vulnerable to climate change.**

**Figure F5.1.** Blue carbon coastal ecosystems—mangroves (**b**), seagrasses (**c**), and coastal wetlands (**d**)—store more carbon belowground in soils and root systems (per hectare) than terrestrial vegetation, with mangroves storing the most carbon per hectare (**a**). They also provide other benefits such as reducing flood risk, supporting subsistence livelihoods, and providing recreational opportunities. However, blue carbon ecosystems are vulnerable to sea level rise, hurricanes, and other extreme events. In (a), black bars indicate the 95% confidence interval (which was unavailable for seagrasses). Figure credit: (a) Pathways Climate Institute. Photo credits: (b) YinYang, iStock/Getty Images Plus via Getty Images; (c) tswinner, iStock/Getty Images Plus via Getty Images; (d) Ken Wiedemann, iStock/Getty Images Plus via Getty Images.

## Additional Benefits

BCEs are located at the interfaces among terrestrial, freshwater, and marine environments. They provide habitat for species, filter fresh water, recycle nutrients and other materials (KM 8.3), and help sustain human communities by providing other benefits, such as dissipating waves, reducing flood risk, and supporting coastal livelihoods, food security, cultural activities, and tourism (KMs 23.2, 30.4; Box 30.5).[18,19] Coastal seagrasses and wetlands provide nursery habitat for young crustaceans and fishes of economic and cultural value[20] and support the status and function of adjacent ecosystems. In addition, seagrasses may mitigate ocean acidification locally, thereby reducing some climate-driven stressors to shellfish and crustaceans.[21,22]

## Effects of Climate Change on Blue Carbon

Sea level rise (SLR) and extreme events are the greatest climate change threats to BCEs.[23] In the past, many BCEs adapted to SLR through belowground root growth, sedimentation, and inland migration, which collectively increased the elevation of BCEs. As SLR accelerates, the ability of BCEs to continue to adapt is uncertain.[24,25] If BCEs cannot adapt to accelerating SLR, their geographical extent will decrease, and their species composition will change.[26] Currently, 43%–48% of wetlands along the Atlantic and Gulf Coasts are vulnerable to SLR, with northern wetlands limited by inland migration capacity and southern wetlands limited by local subsidence, which increases the relative rate of local sea level rise (KM 9.2).[27]

Growth of some plant species may increase in response to a warming climate and increased atmospheric carbon dioxide concentrations. This increased plant growth could locally offset accelerating SLR and allow some BCE species to continue to adapt. However, a 33-year coastal wetland experiment suggests that when SLR reaches a certain rate, plant growth will be hindered, thereby limiting these benefits.[28] This suggests that enhanced plant growth alone may not enable all coastal wetland species to adapt to accelerating SLR.

Human disturbance, SLR, and extreme events can erode and degrade BCEs, reducing carbon storage and potentially releasing previously stored carbon and methane.[29,30,31] If conservation efforts are not undertaken, this release of stored carbon could result in harmful climate change feedbacks.[32,33] For example, accelerating sea level rise would further degrade blue carbon ecosystems, reducing carbon sequestration and releasing stored carbon, which would further increase the rate of ecosystem degradation. Protecting and minimizing degradation of coastal areas to support carbon sequestration can have cascading ecological and societal benefits.[3]

## Emerging Research

Although BCE conservation and restoration have wide-ranging benefits, uncertainties remain regarding carbon sequestration rates across different ecosystems and regions.[34] Research efforts are ongoing to improve methods, measurements, and modeling to fill knowledge gaps related to coastal carbon budgets.[35,36,37]

Seagrasses may mitigate local and/or regional ocean acidification rates by absorbing carbon dioxide and increasing the pH of seawater.[22] However, oceanic conditions are changing rapidly, and additional research is needed to assess this mitigation potential under high ocean acidification rates and warming ocean temperatures (KM 10.1).[38] The effect of ocean acidification on marine ecosystems is expected to vary depending on the combined influence of multiple climate drivers and other factors.[39]

The most effective means of enhancing BCEs and carbon sequestration are increasing local sediment supplies; enabling wetland expansion, including inland migration capacity; and restoring natural tidal conditions.[40] Mechanisms to support these enhancements are location-, ecosystem-, and stressor-dependent, and their success will be affected by past actions such as damming rivers, deforestation, building seawalls and other structures, and encroaching development.[41]

# Traceable Accounts

## *Description of Evidence Base and Research Gaps*

Although much is known about carbon cycling in coastal ecosystems, there are substantial challenges and uncertainties to quantifying carbon storage, carbon storage potential, and carbon sequestration rates across different ecosystems, vegetation types, and locations. Coastal systems are also stressed by natural coastal and climate variability (e.g., erosion, extreme storm events, sea level rise) and other historical and contemporary land uses that affect carbon cycling.[3,26] The extent to which these stressors may impact carbon storage or emissions is uncertain but is important to quantify for improved sequestration assessments.

Finding consistent and comparable data to compare belowground and aboveground carbon storage across coastal and terrestrial ecosystems is challenging. Cooley et al. (2022)[18] presented the most recent data compilation across several research efforts; however, these comparisons among ecosystems used different depths belowground for carbon stock measurements, and some measurements did not separate aboveground and belowground carbon storage or separate biomass carbon storage from soil carbon storage. Soil carbon storage, and the ratio of soil carbon to biomass storage, may indicate the potential of BCEs for carbon storage.

# References


1. Nellemann, C., E. Corcoran, C.M. Duarte, L. Valdés, C. De Young, L. Fonseca, and G. Grimsditch, Eds., 2009: *Blue Carbon*. A Rapid Response Assessment. United Nations Environment Programme, GRID-Arendal. https://www.grida.no/publications/145

2. Macreadie, P.I., A. Anton, J.A. Raven, N. Beaumont, R.M. Connolly, D.A. Friess, J.J. Kelleway, H. Kennedy, T. Kuwae, P.S. Lavery, C.E. Lovelock, D.A. Smale, E.T. Apostolaki, T.B. Atwood, J. Baldock, T.S. Bianchi, G.L. Chmura, B.D. Eyre, J.W. Fourqurean, J.M. Hall-Spencer, M. Huxham, I.E. Hendriks, D. Krause-Jensen, D. Laffoley, T. Luisetti, N. Marbà, P. Masque, K.J. McGlathery, J.P. Megonigal, D. Murdiyarso, B.D. Russell, R. Santos, O. Serrano, B.R. Silliman, K. Watanabe, and C.M. Duarte, 2019: The future of Blue Carbon science. *Nature Communications*, **10** (1), 3998. https://doi.org/10.1038/s41467-019-11693-w

3. Macreadie, P.I., M.D.P. Costa, T.B. Atwood, D.A. Friess, J.J. Kelleway, H. Kennedy, C.E. Lovelock, O. Serrano, and C.M. Duarte, 2021: Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, **2** (12), 826–839. https://doi.org/10.1038/s43017-021-00224-1

4. Song, S., Y. Ding, W. Li, Y. Meng, J. Zhou, R. Gou, C. Zhang, S. Ye, N. Saintilan, K.W. Krauss, S. Crooks, S. Lv, and G. Lin, 2023: Mangrove reforestation provides greater blue carbon benefit than afforestation for mitigating global climate change. *Nature Communications*, **14** (1), 756. https://doi.org/10.1038/s41467-023-36477-1

5. Macreadie, P.I., A.I. Robertson, B. Spinks, M.P. Adams, J.M. Atchison, J. Bell-James, B.A. Bryan, L. Chu, K. Filbee-Dexter, L. Drake, C.M. Duarte, D.A. Friess, F. Gonzalez, R.Q. Grafton, K.J. Helmstedt, M. Kaebernick, J. Kelleway, G.A. Kendrick, H. Kennedy, C.E. Lovelock, J.P. Megonigal, D.T. Maher, E. Pidgeon, A.A. Rogers, R. Sturgiss, S.M. Trevathan-Tackett, M. Wartman, K.A. Wilson, and K. Rogers, 2022: Operationalizing marketable blue carbon. *One Earth*, **5** (5), 485–492. https://doi.org/10.1016/j.oneear.2022.04.005

6. Donofrio, S., P. Maguire, W. Merry, and S. Zwick, 2019: Financing Emissions Reductions for the Future: State of the Voluntary Carbon Markets 2019. Forest Trends' Ecosystem Marketplace, Washington, DC. https://www.forest-trends.org/wp-content/uploads/2019/12/SOVCM2019.pdf

7. Friess, D.A., J. Howard, M. Huxham, P.I. Macreadie, and F. Ross, 2022: Capitalizing on the global financial interest in blue carbon. *PLoS Climate*, **1** (8), e0000061. https://doi.org/10.1371/journal.pclm.0000061

8. Zeng, Y., D.A. Friess, T.V. Sarira, K. Siman, and L.P. Koh, 2021: Global potential and limits of mangrove blue carbon for climate change mitigation. *Current Biology*, **31** (8), 1737–1743. https://doi.org/10.1016/j.cub.2021.01.070

9. Blume, A., A.P. Pertiwi, C.B. Lee, and D. Traganos, 2023: Bahamian seagrass extent and blue carbon accounting using Earth observation. *Frontiers in Marine Science*, **10**, 1058460. https://doi.org/10.3389/fmars.2023.1058460

10. Failler, P., J. Liu, P. Lallemand, and A. March, 2023: Blue accounting approaches in the emerging African blue economy context. *Journal of Sustainability Research*, **5** (1), e230002. https://doi.org/10.20900/jsr20230002

11. Krause, J.R., A. Hinojosa-Corona, A.B. Gray, J.C. Herguera, J. McDonnell, M.V. Schaefer, S.C. Ying, and E.B. Watson, 2022: Beyond habitat boundaries: Organic matter cycling requires a system-wide approach for accurate blue carbon accounting. *Limnology and Oceanography*, **67** (S2), S6–S18. https://doi.org/10.1002/lno.12071

12. IPCC, 2014: *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., T. Krug, K. Tanabe, N. Srivastava, B. Jamsranjav, M. Fukuda, and T. Troxler, Eds. The Intergovernmental Panel on Climate Change, Switzerland. https://www.ipcc.ch/publication/2013-supplement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories-wetlands/

13. Crooks, S., A.E. Sutton-Grier, T.G. Troxler, N. Herold, B. Bernal, L. Schile-Beers, and T. Wirth, 2018: Coastal wetland management as a contribution to the US National Greenhouse Gas Inventory. *Nature Climate Change*, **8** (12), 1109–1112. https://doi.org/10.1038/s41558-018-0345-0

14. Holmquist, J.R., L. Windham-Myers, B. Bernal, K.B. Byrd, S. Crooks, M.E. Gonneea, N. Herold, S.H. Knox, K.D. Kroeger, J. McCombs, J.P. Megonigal, M. Lu, J.T. Morris, A.E. Sutton-Grier, T.G. Troxler, and D.E. Weller, 2018: Uncertainty in United States coastal wetland greenhouse gas inventorying. *Environmental Research Letters*, **13** (11), 115005. https://doi.org/10.1088/1748-9326/aae157

15. Campbell, A.D., L. Fatoyinbo, L. Goldberg, and D. Lagomasino, 2022: Global hotspots of salt marsh change and carbon emissions. *Nature*, **612** (7941), 701–706. https://doi.org/10.1038/s41586-022-05355-z

16. Lovelock, C.E. and C.M. Duarte, 2019: Dimensions of blue carbon and emerging perspectives. *Biology Letters*, **15** (3), 20180781. https://doi.org/10.1098/rsbl.2018.0781

17. Teng, Y. and D. Zhang, 2018: Long-term viability of carbon sequestration in deep-sea sediments. *Science Advances*, **4** (7), 6588. https://doi.org/10.1126/sciadv.aao6588

18. Cooley, S., D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehiwet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, and M. Skern-Mauritzen, 2022: Ch. 3. Oceans and coastal ecosystems and their services. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 379–550. https://doi.org/10.1017/9781009325844.005

19. Quiros, T.E.A.L., K. Sudo, R.V. Ramilo, H.G. Garay, M.P.G. Soniega, A. Baloloy, A. Blanco, A. Tamondong, K. Nadaoka, and M. Nakaoka, 2021: Blue carbon ecosystem services through a vulnerability lens: Opportunities to reduce social vulnerability in fishing communities. *Frontiers in Marine Science*, **8**, 671753. https://doi.org/10.3389/fmars.2021.671753

20. Lefcheck, J.S., B.B. Hughes, A.J. Johnson, B.W. Pfirrmann, D.B. Rasher, A.R. Smyth, B.L. Williams, M.W. Beck, and R.J. Orth, 2019: Are coastal habitats important nurseries? A meta-analysis. *Conservation Letters*, **12** (4), e12645. https://doi.org/10.1111/conl.12645

21. Dickinson, G.H., S. Bejerano, T. Salvador, C. Makdisi, S. Patel, W.C. Long, K.M. Swiney, R.J. Foy, B.V. Steffel, K.E. Smith, and R.B. Aronson, 2021: Ocean acidification alters properties of the exoskeleton in adult Tanner crabs, *Chionoecetes bairdi*. *Journal of Experimental Biology*, **224** (3), 232819. https://doi.org/10.1242/jeb.232819

22. Ricart, A.M., M. Ward, T.M. Hill, E. Sanford, K.J. Kroeker, Y. Takeshita, S. Merolla, P. Shukla, A.T. Ninokawa, K. Elsmore, and B. Gaylord, 2021: Coast-wide evidence of low pH amelioration by seagrass ecosystems. *Global Change Biology*, **27** (11), 2580–2591. https://doi.org/10.1111/gcb.15594

23. Osland, M.J., B. Chivoiu, N.M. Enwright, K.M. Thorne, G.R. Guntenspergen, J.B. Grace, L.L. Dale, W. Brooks, N. Herold, J.W. Day, F.H. Sklar, and C.M. Swarzenzki, 2022: Migration and transformation of coastal wetlands in response to rising seas. *Science Advances*, **8** (26), 5174. https://doi.org/10.1126/sciadv.abo5174

24. van Dobben, H.F., A.V. de Groot, and J.P. Bakker, 2022: Salt marsh accretion with and without deep soil subsidence as a proxy for sea-level rise. *Estuaries and Coasts*, **45** (6), 1562–1582. https://doi.org/10.1007/s12237-021-01034-w

25. Wang, F., X. Lu, C.J. Sanders, and J. Tang, 2019: Tidal wetland resilience to sea level rise increases their carbon sequestration capacity in United States. *Nature Communications*, **10** (1), 5434. https://doi.org/10.1038/s41467-019-13294-z

26. Warnell, K., L. Olander, and C. Currin, 2022: Sea level rise drives carbon and habitat loss in the U.S. mid-Atlantic coastal zone. *PLOS Climate*, **1** (6), e0000044. https://doi.org/10.1371/journal.pclm.0000044

27. Holmquist, J.R., L.N. Brown, and G.M. MacDonald, 2021: Localized scenarios and latitudinal patterns of vertical and lateral resilience of tidal marshes to sea-level rise in the contiguous United States. *Earth's Future*, **9** (6), e2020EF001804. https://doi.org/10.1029/2020ef001804

28. Zhu, C., J.A. Langley, L.H. Ziska, D.R. Cahoon, and J.P. Megonigal, 2022: Accelerated sea-level rise is suppressing $CO_2$ stimulation of tidal marsh productivity: A 33-year study. *Science Advances*, **8** (20), 0054. https://doi.org/10.1126/sciadv.abn0054

29. Lovelock, C.E. and R. Reef, 2020: Variable impacts of climate change on blue carbon. *One Earth*, **3** (2), 195–211. https://doi.org/10.1016/j.oneear.2020.07.010

30. Rosentreter, J.A., A.V. Borges, B.R. Deemer, M.A. Holgerson, S. Liu, C. Song, J. Melack, P.A. Raymond, C.M. Duarte, G.H. Allen, D. Olefeldt, B. Poulter, T.I. Battin, and B.D. Eyre, 2021: Half of global methane emissions come from highly variable aquatic ecosystem sources. *Nature Geoscience*, **14** (4), 225–230. https://doi.org/10.1038/s41561-021-00715-2

31. Zou, J., A.D. Ziegler, D. Chen, G. McNicol, P. Ciais, X. Jiang, C. Zheng, J. Wu, J. Wu, Z. Lin, X. He, L.E. Brown, J. Holden, Z. Zhang, S.J. Ramchunder, A. Chen, and Z. Zeng, 2022: Rewetting global wetlands effectively reduces major greenhouse gas emissions. *Nature Geoscience*, **15** (8), 627–632. https://doi.org/10.1038/s41561-022-00989-0

32. Nisbet, E.G., 2023: Climate feedback on methane from wetlands. *Nature Climate Change*, **13** (5), 421–422. https://doi.org/10.1038/s41558-023-01634-3

33. Zwerschke, N., C.J. Sands, A. Roman-Gonzalez, D.K.A. Barnes, A. Guzzi, S. Jenkins, C. Muñoz-Ramírez, and J. Scourse, 2022: Quantification of blue carbon pathways contributing to negative feedback on climate change following glacier retreat in West Antarctic fjords. *Global Change Biology*, **28** (1), 8–20. https://doi.org/10.1111/gcb.15898

34. Williamson, P. and J.-P. Gattuso, 2022: Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. *Frontiers in Climate*, **4**, 853666. https://doi.org/10.3389/fclim.2022.853666

35. Bogard, M.J., B.A. Bergamaschi, D.E. Butman, F. Anderson, S.H. Knox, and L. Windham-Myers, 2020: Hydrologic export is a major component of coastal wetland carbon budgets. *Global Biogeochemical Cycles*, **34** (8), e2019GB006430. https://doi.org/10.1029/2019gb006430

36. Marchand, C., F. David, A. Jacotot, A. Leopold, and X. Ouyang, 2022: Ch. 3. $CO_2$ and $CH_4$ emissions from coastal wetland soils. In: *Carbon Mineralization in Coastal Wetlands*. Ouyang, X., S.Y. Lee, D.Y.F. Lai, and C. Marchand, Eds. Elsevier, 55–91. https://doi.org/10.1016/b978-0-12-819220-7.00006-6

37. Ouyang, X. and S.Y. Lee, 2020: Improved estimates on global carbon stock and carbon pools in tidal wetlands. *Nature Communications*, **11** (1), 317. https://doi.org/10.1038/s41467-019-14120-2

38. Bergstrom, E., J. Silva, C. Martins, and P. Horta, 2019: Seagrass can mitigate negative ocean acidification effects on calcifying algae. *Scientific Reports*, **9** (1), 1932. https://doi.org/10.1038/s41598-018-35670-3

39. Gao, K., J. Beardall, D.-P. Häder, J.M. Hall-Spencer, G. Gao, and D.A. Hutchins, 2019: Effects of ocean acidification on marine photosynthetic organisms under the concurrent influences of warming, UV radiation, and deoxygenation. *Frontiers in Marine Science*, **6**, 322. https://doi.org/10.3389/fmars.2019.00322

40. Moritsch, M.M., K.B. Byrd, M. Davis, A. Good, J.Z. Drexler, J.T. Morris, I. Woo, L. Windham-Myers, E. Grossman, G. Nakai, K.L. Poppe, and J.M. Rybczyk, 2022: Can coastal habitats rise to the challenge? Resilience of estuarine habitats, carbon accumulation, and economic value to sea-level rise in a Puget Sound estuary. *Estuaries and Coasts*, **45** (8), 2293–2309. https://doi.org/10.1007/s12237-022-01087-5

41. Morton, R.A., 2003: An Overview of Coastal Land Loss: With Emphasis on the Southeastern United States. USGS Open-File Report 03-337. U.S. Geological Survey. https://pubs.usgs.gov/of/2003/of03-337/

Fifth National Climate Assessment: Appendix 1

# Assessment Development Process

# Appendix 1. Assessment Development Process

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# A1.1. The US Global Change Research Program

Founded by Presidential Initiative in 1989 and codified by the Global Change Research Act of 1990,[1] the US Global Change Research Program (USGCRP) is charged with developing and coordinating "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

USGCRP operates under the direction of the National Science and Technology Council as a confederation of 14 federal departments and agencies and is overseen by the White House Office of Science and Technology Policy (OSTP). The Subcommittee on Global Change Research (SGCR) oversees USGCRP's activities and coordinates interagency activities through the USGCRP National Coordination Office and informal interagency working groups. More information on USGCRP activities can be found at www.globalchange.gov and in the Decadal Strategic Plan.[2]

# A1.2. Roles and Participants in NCA5

The Fifth National Climate Assessment (NCA5) followed a similar structure and governance model as the previous NCA, with roles and responsibilities described in Table A1.1.

**Table A1.1. Descriptions of Roles for NCA5 Participants**

| Role | Description |
|---|---|
| **Federal Steering Committee (FSC)** | The FSC consisted of one representative from each USGCRP member agency. In consultation with the SGCR, the FSC was responsible for selecting CLAs, CLs, and REs; determining scope and content; and overseeing development and production of NCA5, including ensuring that the process adhered to principles of engagement and transparency. |
| **Federal Coordinating Lead Author (CLA) and Agency Chapter Lead (ACL)** | CLAs served as the federal coordinating lead for each chapter. ACLs provided additional agency input to chapter teams. Both CLAs and ACLs were responsible for coordination across chapters to ensure consistency and accuracy throughout the report and to ensure that chapters adhered to author guidance. CLAs were responsible for recommending CLs to the FSC. The FSC was responsible for reviewing and approving CLs. |
| **Chapter Lead Author (CL)** | CLs were responsible for the ultimate delivery of their chapter for approval and publication. These responsibilities included selecting a diverse and qualified author team and overseeing all aspects of development, assessment, writing, and editing of their chapter. |
| **Chapter Author (CA)** | CAs contributed writing, developed figures, responded to comments, and revised chapter drafts under the direction of the CLs. Each chapter's Key Messages represent the consensus of the CAs and CL. |
| **Technical Contributor (TC)** | TCs provided discrete, specific technical contributions on an as-needed basis, as identified by the CL. TCs did not participate in the consensus process of developing Key Messages. |

| Role | Description |
|---|---|
| Review Editor (RE) | REs, selected by the FSC from a public call for nominees, were responsible for ensuring that all substantive public and peer-review comments were appropriately addressed and documented by author teams. |
| Staff Point of Contact (POC) | USGCRP National Coordination Office staff filled the roles of POCs, providing administrative support, chapter coordination, and guidance throughout report development. |
| Technical Support Unit (TSU) | The NOAA TSU supported climate science data analysis; editing; figure development; data management and documentation; web design and development; and graphic design, layout, and other production activities. |

# A1.3. Creating the NCA5 Report

The NCA5 development process launched in February 2020 with the seating of the NCA5 Federal Steering Committee (FSC). The FSC decided to follow development, review, and publication processes similar to those used for NCA4, with some changes intended to increase the transparency, engagement, and usability of NCA5. Details on the NCA4 assessment development process were outlined in NCA4's Process Appendix[3] and are not repeated here. Additional process changes for NCA5 are described below.

## *Broadened Participation*

More than 750 experts volunteered as chapter leads, authors, technical contributors, and review editors in NCA5 (Figure A1.1), a significant increase in participation compared to previous Assessments. In response to public comments calling for more diverse author teams and inclusion of a broader range of expertise, the number of all-federal author teams was reduced to three chapters. With few exceptions, contributors were limited to serving in a single role (Table A1.1) to ensure that as many people as possible could participate in NCA5.

### Authors of NCA5

**Hundreds of experts from all across the US came together to develop NCA5.**

**Figure A1.1.** NCA5 was made possible by approximately 500 authors, 250 technical contributors, 41 review editors, 13 chapter coordinators, 14 Federal Steering Committee members, 18 peer reviewers, more than 40 staff members, thousands of participants in public engagement events, hundreds of public commenters and agency reviewers, and approximately 800 artists from every state and territory of the US. This picture is a subset of authors, coordinators, and review editors who attended the second all-authors meeting in Washington, DC, on April 4, 2023. Photo credit: Christopher Avery, USGCRP/ICF.

Chapter leads (CLs) were provided with multiple criteria to consider when selecting their author teams. All authors were required to have the scientific expertise needed to contribute meaningfully to the chapter. CLs were required to consider nominees submitted through a public call for author nominations but were not limited to selecting authors from those nominees. Additionally, CLs were required to build diverse teams by considering a range of disciplines (physical, social, biological sciences, Indigenous Knowledge, science communication, etc.), a broad array of experience (practitioner, academic, etc.), and diverse lived experiences and perspectives, including geographic location, career stage, professional organization type, race, ethnicity, gender, and past assessment experience. Regional chapters were strongly encouraged to include authors from each state within the region. Authors and contributors to NCA5 included experts from all 50 states, Puerto Rico, the US Virgin Islands, Guam, and Palau.

## *Increased Public Engagement Opportunities*

Public engagement seeks to help authors understand the interests and concerns of NCA readers and ensures that the final report represents the priorities and needs of decision-makers across the country. In addition to taking public comment on the draft Assessment in the fall of 2022, NCA5 featured a new opportunity for public comment on the chapter's initial annotated outlines, or Zero Order Drafts.[4] A "how-to" video and step-by-step guide were developed to facilitate the public comment process. During this public comment period (January and February 2022), USGCRP also hosted 34 virtual public engagement workshops that were free and open to the public (Figure A1.2). During the workshops, authors spoke with members of the public about the draft chapter outlines and identified priority issues relevant to the chapter.

In some cases, workshop participants challenged authors to reconsider the key topics covered in the report or shifted authors' thinking about specific areas of emerging concern. In other cases, the workshops prompted authors to forge more connections across the report and with other chapter teams or identified where chapter teams had a gap in needed expertise.

### NCA5 Zero Order Draft Public Engagement Workshops

**Early public engagement helped inform the scope of NCA5.**

**Figure A1.2.** The NCA5 Public Engagement Workshops attracted more than 7,000 registrations, with approximately 2,800 people participating via plenary discussions, breakout rooms, and interactive collaborative tools. The charts above show the self-identified organizational type (**left**) and region (**right**) of workshop registrants as the percentage of total registrants (not population weighted). For example, participants included more than 400 people who self-identified as being affiliated with a Tribe. Figure credit: USGCRP/ICF.

## Updated Guidance to Better Incorporate Indigenous Knowledge

NCA5 leadership participated in three Tribal consultations and one Tribal listening session and took public input on the use of Indigenous Knowledge in federal decision-making.[5] Based on feedback received during a public comment process for the federal guidance,[6] the NCA guidance to authors on Information Quality was updated (see App. 2). Authors were also provided training on writing about Indigenous perspectives and using Indigenous Knowledge in author orientation and chapter leadership meetings.

## Improved Diversity, Equity, Inclusion, Justice, and Accessibility

Beyond the steps listed above to ensure author diversity and widespread public engagement, NCA5 took several steps to improve the inclusive nature of the NCA development process, advance the conversation around equity and justice, and enhance accessibility of NCA5 products.

- For the first time, a code of conduct was instituted for all NCA participants to help ensure that all participants could engage in an inclusive, respectful, and safe environment.[7]
- Spanish translation was provided during the Caribbean public engagement workshop and of the draft Caribbean chapter released for public comment. For the first time, the entire Assessment report will be translated into Spanish.
- Throughout the report development process, USGCRP encouraged discussions around equity and justice topics. Authors were asked to consider the justice implications of climate change so as to make the report more broadly representative and inclusive of historically underrepresented communities.
- NCA5 represents the first time that the website for NCA is the report of record. As a result, this report was developed and designed to be delivered as a digital product. This website is designed to follow new standards of the US Web Design System[8] under the 21st Century Integrated Digital Experience Act of 2018.[9]
- NCA5 built on the success of NCA4 in its compliance with Section 508 of the Rehabilitation Act of 1973 to improve accessibility and usability by the broadest possible audience, including people with visual or physical limitations. For instance, guidance was provided to authors to avoid complex or nested tables and alternative text was developed for all images to support the use of screen readers. Graphics are also designed to be readable for users with color-perception challenges by using appropriate color schemes and visual presentations.

## Strengthened Documentation Processes

Based on laws (e.g., the Foundations for Evidence-Based Policymaking Act, or Evidence Act of 2018;[10] see Appendix 2 for additional information) and transparency best practices that evolved since NCA4, processes for documenting multiple aspects of supporting materials were strengthened for NCA5. Authors were required to disclaim any intellectual property created in the process of producing this report to ensure that the report content could be released under the Creative Commons 1.0 Universal Public Domain Dedication (CC0 1.0). Additionally, NCA4's gold-standard process for metadata tracking and verification was improved, with software updates and a user manual to aid authors in their documentation process. Additional details on this process can be found in Appendix 2.

## Creative Communications

Science communication support throughout the writing process was provided by the Technical Support Unit (TSU). Early author orientation and trainings emphasized TSU's data visualization and graphic design support for figure development, with the goal of including high-quality figures throughout NCA5 to convey important messages and supplement the text. The final report contains 388 figures.

USGCRP pursued several art–science collaborations throughout the NCA5 process. On October 11, 2022, USGCRP announced an open call for visual artwork. The call, which was open to youth and adults, invited works around the themes of NCA5 that depict climate change impacts and responses and that reflect the lived experience of people across the country. Five award winners and 92 finalists from the approximately 800 submissions received are featured in the Art × Climate Gallery and throughout the report.[11] Artwork that appears in chapters is denoted by a gray background and accompanied by the artist's statement. In addition, USGCRP collaborated with the National Endowment for the Arts and the Library of Congress to include the bespoke poem "Startlement," written for NCA5 by the 24th US Poet Laureate, Ada Limón.

## *Accessible Climate Data*

An interactive online atlas (NCA5 Atlas) was developed to provide additional resources for climate impact and resilience planning, with a selection of climate variables curated for each US region. These variables were produced using the same methodology as the downscaled precipitation and temperature projections used throughout NCA5 (App. 3). The Atlas includes interactive maps, plain language descriptions, and links to subregional climate products such as the NOAA State Climate Summaries and the USGCRP Climate Indicators (App. 4). The NCA5 Atlas was created through a collaboration between NOAA and ESRI (Environmental Systems Research Institute Inc.) that complemented other agency-supported planning initiatives, including the Climate Explorer, the Interagency Sea Level Rise Scenario Tool, and the Climate Mapping for Resilience and Adaptation portal.

# References


1. Global Change Research Act of 1990. 101st Congress, Pub. L. No. 101-606, 104 Stat. 3096–3104, November 16, 1990. https://www.congress.gov/bill/101st-congress/senate-bill/169/text

2. USGCRP, 2022: The U.S. Global Change Research Program 2022–2031 Strategic Plan. U.S. Global Change Research Program, Washington, DC. https://doi.org/10.7930/usgcrp-2022-2031-strategic-plan

3. Avery, C.W., D.R. Reidmiller, T.S. Carter, K.L.M. Lewis, and K. Reeves, 2018: Appendix 1. Report development process. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1387–1409. https://doi.org/10.7930/nca4.2018.ap1

4. NOAA, 2022: Public comment on the annotated outline of the Fifth National Climate Assessment. *Federal Register*, **85** (5), 940–941. https://www.govinfo.gov/content/pkg/FR-2022-01-07/pdf/2022-00097.pdf

5. Nelson, A. and B. Mallory, 2022: Announcing Tribal Consultation and public input opportunities on Indigenous Traditional Ecological Knowledge in Federal policy. The White House, Washington, DC, March 7, 2022. https://www.whitehouse.gov/ostp/news-updates/2022/03/07/announcing-tribal-consultation-and-public-input-opportunities-on-indigenous-traditional-ecological-knowledge-in-federal-policy/

6. OSTP, 2022: Guidance for Federal Departments and Agencies on Indigenous Knowledge. White House Office of Science and Technology Policy, Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2022/12/ostp-ceq-ik-guidance.pdf

7. USGCRP, n.d.: Code of Conduct. U.S. Global Change Research Program, accessed May 23, 2023. https://www.globalchange.gov/content/us-global-change-research-program-code-conduct

8. GSA, 2023: U.S. Web Design System. U.S. General Services Administration, accessed April 12, 2023. https://tech.gsa.gov/guides/us_web_design_system/

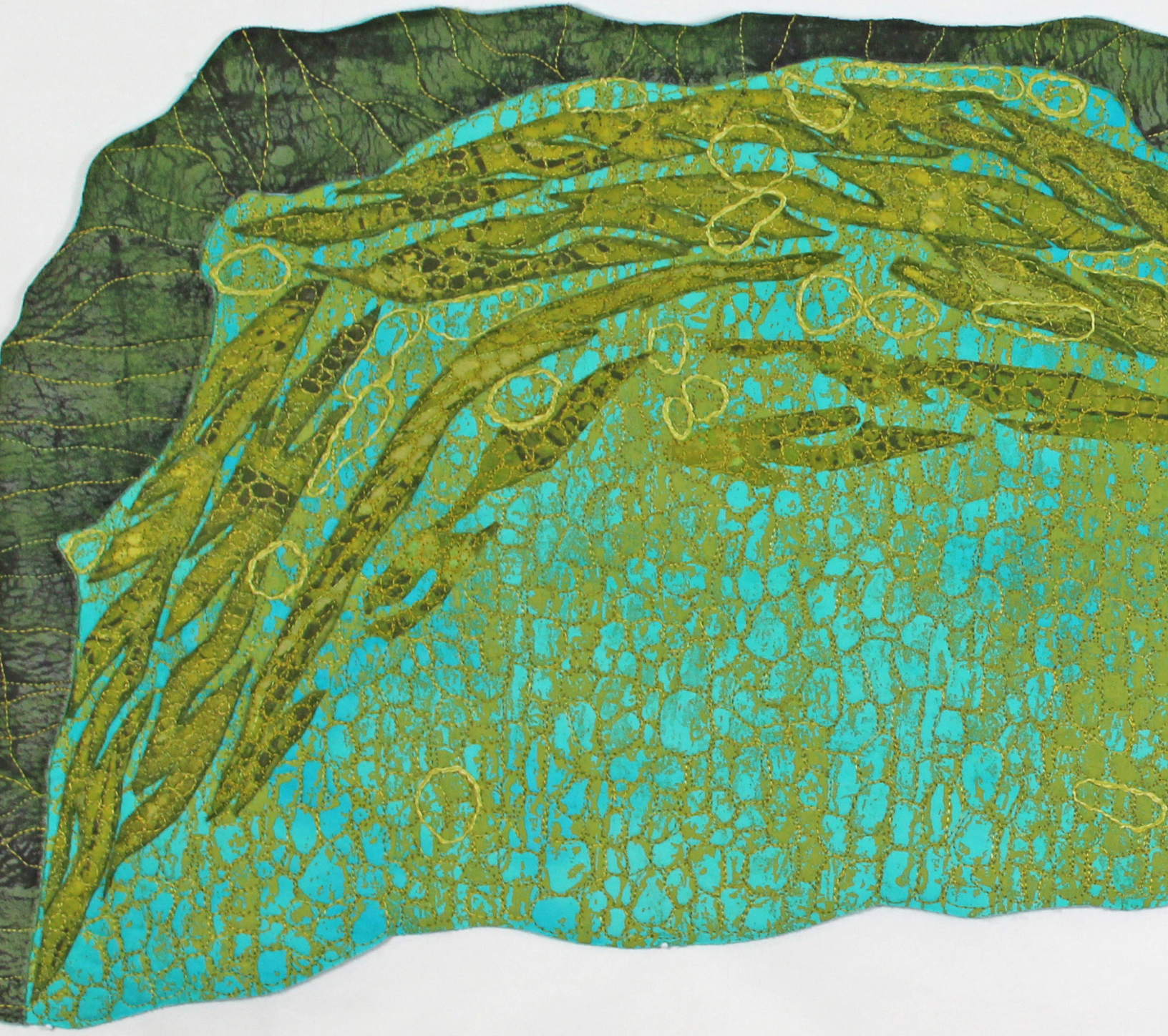
9. 21st Century Integrated Digital Experience Act. Pub. L. No. 115-336, 132 Stat. 5025, December 20, 2018. https://digital.gov/resources/21st-century-integrated-digital-experience-act/

10. Foundations for Evidence-Based Policymaking Act of 2018. H.R.4174, 115th Congress, Pub. L. No. 115-435, 132 Stat. 5529–5557, January 14, 2019. https://www.congress.gov/bill/115th-congress/house-bill/4174/text

11. OSTP, 2023: White House Office of Science and Technology Policy announces National Climate Assessment art submission award winners. White House Office of Science and Technology Policy, Washington, DC, June 9, 2023. https://www.whitehouse.gov/ostp/news-updates/2023/06/09/white-house-office-of-science-and-technology-policy-announces-national-climate-assessment-art-submission-award-winners/

Fifth National Climate Assessment: Appendix 2

# Information Quality



# Appendix 2. Information Quality

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# A.2.1. Introduction

The National Climate Assessment (NCA) is required by law to meet the highest information quality standards set by the Federal Government. Specific information quality requirements are set out by the Information Quality Act (IQA),[1] the Office of Management and Budget (OMB) Final Information Quality Bulletin for Peer Review for highly influential scientific assessments (HISA),[2] and the Foundations for Evidence-Based Policymaking Act (EBPA, or Evidence Act 2018).[3] Because NOAA is the administrative agency for NCA5, its agency guidelines under these federal standards serve as the guiding principles for the Assessment. Information quality compliance is affirmed by the NCA Information Quality Officer, furnished by the administrative lead agency.

The **IQA** ensures that the Assessment data and information are of a sufficient quality by meeting standards of *objectivity*, *utility*, and *integrity*. This includes the requirement for information in the Assessment to demonstrate a capability of being reasonably *reproduced*. For analytic data, reproducibility means that independent analysis of the original or supporting data using identical methods would generate similar analytic results to an acceptable degree of precision.

The **OMB Final Information Quality Bulletin for Peer Review** establishes guidance to enhance the practice of peer review of government science documents in order to increase the quality and credibility of scientific information generated across the Federal Government. The bulletin sets the minimum peer-review requirements for documents with the HISA designation, including the National Climate Assessment.

The **Evidence Act** expands on prior open government policy initiatives and public access to agency data assets. It requires that all federal data assets and supporting information be open by default, distributed under an open license, and published as machine-readable—subject to legal exemptions for privacy sensitivities and/or intellectual property rights.

# A2.2. Source Materials

Sources (or source materials) broadly include all information used in the Assessment. Authors must consider information quality when deciding whether to use a given source in a chapter. Information quality standards must be met any time a source is associated with the Assessment, including incorporating the source into the chapter, citing the source, or linking to the source.

Authors compiled information sources from peer-reviewed literature, other literature, Indigenous Knowledge, and other expert and local knowledge. Authors were provided with additional Federal guidance on use of Indigenous Knowledge.[4] A fifth type of information that may be used in the NCA is climate data processed and prepared for authors by NOAA's Technical Support Unit (TSU; see App. 3). Authors were advised to evaluate each source based on the following attributes:

- **Applicability and Utility**: The source is important, relevant, and useful for its intended audience (not only from the author's perspective but also from the public's).
- **Transparency and Traceability**: The source material, the methods supporting conclusions, and the evaluation of the source are documented and clear.
- **Objectivity**: The purpose, methods used to create the source material, presentation, substance, and interpretation of conclusions are clear, accurate, reliable, and unbiased.
- **Integrity and Security**: The source material will remain reasonably protected and intact over time, and both the information and the owners of the information are respected.
- **Reproducibility**: Procedures surrounding source materials are documented such that they can be reproduced, with checks for robustness on non-reproducible data.

While development of an NCA chapter often involves a comprehensive literature review, not every source evaluated in the report development process will be cited in the NCA chapters. An important responsibility of the authors is to determine which sources are most useful to include in the Assessment. References cited in the Assessment are those that are highly relevant and critical to the understanding of the intended users or audience of the Assessment.

To assist in source evaluation, authors were provided Information Quality Decision Pathways to determine whether a source met these standards and could be cited in the NCA. Additional source information came from previous Assessments and technical input reports; feedback from 34 public engagement workshops (see App. 1) and other engagement events; expert awareness of the literature from authors; chapter-specific submissions of technical resources and relevant literature to author teams; and a public request for scientific and technical inputs. Information submissions were requested via a Federal Register Notice published by NASA on behalf of the US Global Change Research Program in 2020.[5] This notice called for the public to submit "relevant scientific and/or technical research studies—including observed, modeled, and/or projected global change and climate science information, as well as societal drivers, vulnerability, impacts, and responses." The public call specifically encouraged submissions of regional information and information for cross-cutting or new topics since NCA4. This public call for information was open from October 15, 2020, through January 31, 2023.

The final report cites approximately 8,300 sources meeting the IQA requirements.

## A2.3. Data and Metadata Standards

In addition to being evaluated on the attributes listed in the Source Materials section above, information based on data (including figures) must adhere to the standards of reproducibility and openness. To meet these requirements, NCA5 collected figure and data sources; dataset, analysis, and visualization methods; and hardware and software metadata (details about the underlying data and information), adhering to NOAA's implementation of ISO-19115 documentation standards.[6] All metadata is made openly accessible as a component of the final report and demonstrates NCA5 compliance with information quality standards.

# References


1. NOAA, 2021: Information Quality Guidelines. National Oceanic and Atmospheric Administration. https://www.noaa.gov/organization/information-technology/policy-oversight/information-quality/information-quality-guidelines

2. OMB, 2004: Final Information Quality Bulletin for Peer Review. M-05-03. U.S. Office of Management and Budget, Washington, DC. https://obamawhitehouse.archives.gov/sites/default/files/omb/assets/omb/memoranda/fy2005/m05-03.pdf

3. Foundations for Evidence-Based Policymaking Act of 2018. H.R.4174, 115th Congress, Pub. L. No. 115-435, 132 Stat. 5529–5557, January 14, 2019. https://www.congress.gov/bill/115th-congress/house-bill/4174/text

4. OSTP, 2022: Guidance for Federal Departments and Agencies on Indigenous Knowledge. White House Office of Science and Technology Policy, Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2022/12/ostp-ceq-ik-guidance.pdf

5. NASA, 2020: Request for public nominations for authors and scientific/technical inputs and notice of planned public engagement opportunities for the Fifth National Climate Assessment. *Federal Register*, **85** (200), 65433–65435. https://www.federalregister.gov/documents/2020/10/15/2020-22729/request-for-public-nominations-for-authors-and-scientifictechnical-inputs-and-notice-of-planned

6. ISO, 2014: Geographic Information—Metadata—Part 1: Fundamentals. ISO 19115-1:2014. International Organization for Standardization, 167 pp. https://www.iso.org/standard/53798.html

Fifth National Climate Assessment: Appendix 3

# Scenarios and Datasets

# Appendix 3. Scenarios and Datasets

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# A3.1. Scenarios and Climate Model Output

Scenarios are descriptions of how conditions may develop over time based on clear and consistent assumptions about key drivers of change.[1] For example, scenarios can describe future emissions, population, energy, and land use to answer questions such as How much more greenhouse gases will humans emit? How will populations grow or move? How will we use land for agriculture, forestry, or cities?

Climate models use scenarios to describe the plausible evolution of human and natural factors that affect the future of Earth's climate system. Climate model output is neither a forecast nor prediction but is referred to as a projection. Climate projections are conditional: when or if we reach a particular outcome is dependent on both human choices and the complex ways in which the climate system responds to those choices. Scenarios and climate model projections allow us to explore how we answer questions about the future and the potential implications of choices made over time. These tools have evolved and improved over time, but they are limited by the current state of knowledge and the necessary simplifications models make in representing Earth's complex climate system.

The state of the science represented in the National Climate Assessment (NCA) is always evolving, often at different paces in different fields. No one set of models, scenarios, or climate projections was implemented across NCA5. Authors could assess and reference any climate scenarios that met legally required evidence quality standards (App. 2). These included, but were not limited to, the Representative Concentration Pathways (RCPs), which were used in Phase 5 of the Coupled Model Intercomparison Project (CMIP5), and a more recent set of scenarios that integrated Shared Socioeconomic Pathways (SSPs).[2,3,4] A set of SSP-RCP combinations was used in CMIP Phase 6 (CMIP6) international model experiments.[3,4,5] In NCA5, Chapter 3 provides a description of SSPs along with a graphic representation of scenario development (Figure 3.4), and the Guide to the Report provides a list of descriptive terms for the RCP and SSP scenarios that are commonly referenced in the report text (Table 3). For certain topics or impact studies, scenarios that preceded the RCPs may be relevant, such as those from the Special Report on Emissions Scenarios (SRES).[6] Similar to the RCPs and SSPs, the SRES scenarios include a set of consistent assumptions that translate into a range of carbon emissions and carbon dioxide concentrations; however, the SRES do not include a net-negative emissions scenario (Figure 33.19 in Walsh et al. 2014[7]). For a more in-depth discussion of emissions scenarios, RCPs, and SSPs, see Chapter 4 of Volume I of the *Fourth National Climate Assessment*.[8]

Overall, CMIP6 models show some specific improvements over CMIP5 in their representation of Earth system processes—mainly due to the fact that more models include biological and chemical interactions as well as higher resolution (Figure TS.2, Section TS.1.2.2 in Arias et al. 2021[9]).[10] Importantly, projections can vary based on the particular climate models and scenarios used, assumptions or parameters employed within those models and scenarios, and methods used to analyze or interpret model outputs. For instance, some CMIP6 models show a particularly large global temperature response to increasing atmospheric carbon dioxide concentrations—a response that is not considered to be realistic (KM 3.1; e.g., Meehl et al. 2020;[11] Nijsse et al. 2020[12]). Scientists can use different methods to account for potential model biases in the temperature response and other climate system changes.[13,14] When comparing projections across NCA5 or with another assessment, it is critical to understand how the methodologies underlying the findings may differ. Supporting information for NCA5 findings can be found in the chapter text, cited references, Traceable Accounts, or figure captions and metadata—all available via the report website.

### Box A3.1. Projecting Climate Impacts Beyond 100 Years Into the Future

Climate change will not end in 2100. However, there is currently a limited number of climate studies with projections that extend past the year 2100. The lack of scenarios for emissions or land use that extend past 2100 constrains the NCA5 authors' ability to present or assess projections 100 years in the future as mandated by the Global Change Research Act of 1990.[15,16] One notable exception is the sea level rise (SLR) scenarios described in this appendix and in Chapter 9, which do extend past 2100 for the contiguous United States. To understand impacts at the century scale and beyond, authors could evaluate potential climate system changes based on applied laws of physics, Earth system dynamics, and extrapolation of climate system change indicators. Additionally, very high climate scenarios, such as RCP8.5 and SSP5-8.5, can be useful tools when considering a range of plausible greenhouse gas concentrations past 2100.[17,18]

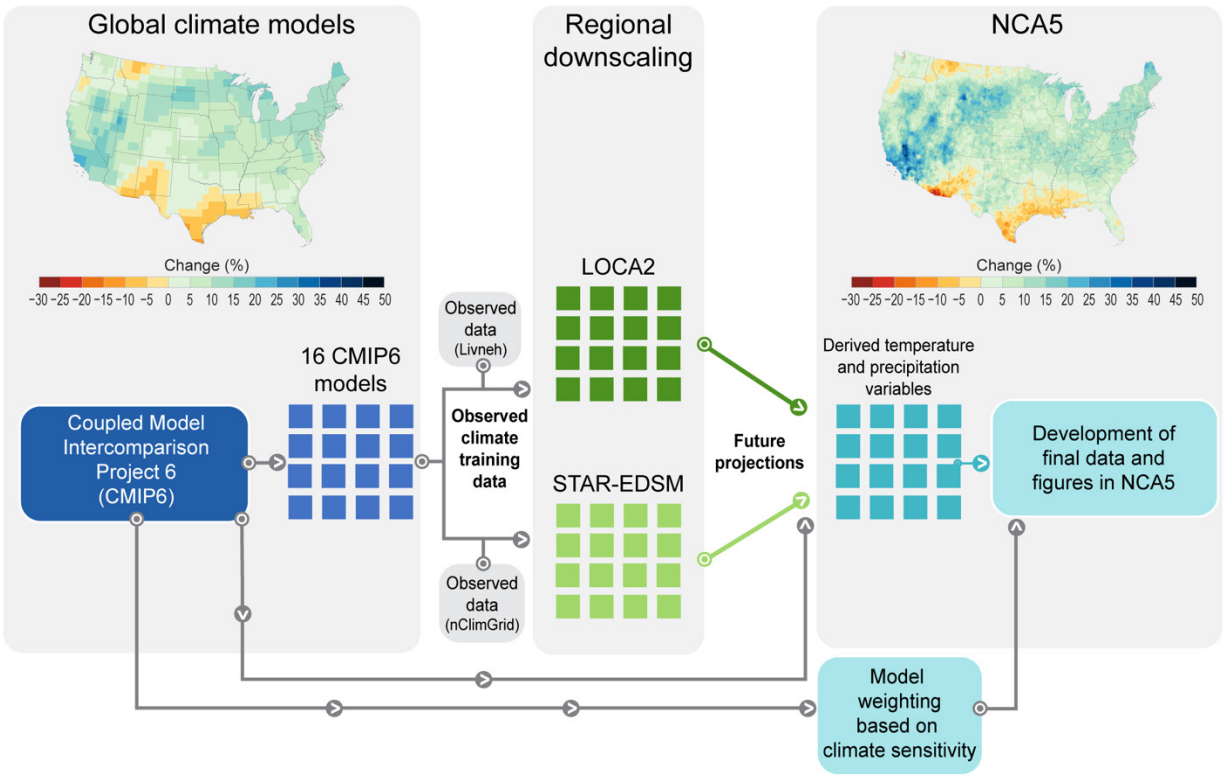
## A3.2. Projected Climate Variables

The NOAA Technical Support Unit (TSU) provided authors with projected climate variable information from 43 CMIP6 models using a set of five SSP-RCP scenarios, which were described in a reference guide provided to authors to ensure consistent terminology throughout NCA5 (see Guide to the Report). Depending on author team requests and variable availability, in some circumstances the TSU selected a smaller number of CMIP6 models and scenarios from the larger ensemble (global climate models box in Figure A3.1).

To provide higher-resolution projections at national or subnational scales, 16 global CMIP6 models were downscaled using historically trained computer algorithms (statistical downscaling) and model weighting based on equilibrium climate sensitivity (Figure A3.1). Two datasets that employed different statistical downscaling methods were used to develop gridded temperature and precipitation datasets for NCA5: the Localized Constructed Analogs Version 2 (LOCA2)[19] and Seasonal Trends and Analysis of Residuals, Empirical-Statistical Downscaling Model (STAR-ESDM)[20,21] (regional downscaling box in Figure A3.1). A collection (ensemble) of models is often used to show an uncertainty range. LOCA2 and STAR-ESDM were applied to 16 CMIP6 models, and downscaled outputs were weighted based on CMIP6 climate sensitivity through Bayesian model averaging.[22,23,24,25] Projections of changes in average and extreme temperature and precipitation were made available to NCA5 authors for national and subnational scales spanning the entire 21st century (NCA5 box in Figure A3.1).

Development of NCA5 overlapped with CMIP6 data releases, limiting the availability of downscaled CMIP6 climate projections. While STAR-ESDM also provided downscaled data for selected individual weather stations, there remains an overall gap in climate projections for geographies outside the contiguous United States, including the regions covered by the Alaska, US Caribbean, and Hawai'i and the US-affiliated Pacific Islands chapters. Authors were also provided guidance on how to access regional datasets or dynamically downscaled data from the CMIP5 Coordinated Regional Climate Downscaling Experiment to include data for these regions where available.[26,27]

## Downscaling Global Climate Model Data for NCA5




**Global model data were downscaled and weighted to generate higher-resolution climate projections.**

**Figure A3.1.** This flowchart shows the steps taken to downscale low-resolution global data from Phase 6 of the Coupled Model Intercomparison Project (CMIP6; **left side of the diagram**) to bias-adjusted high-resolution NCA5 products (**right side of the diagram**). Two downscaling algorithms (**center of the diagram**)—the Localized Constructed Analogs Version 2 (LOCA2) and Seasonal Trends and Analysis of Residuals, Empirical-Statistical Downscaling Model (STAR-ESDM)—were developed for each of the 16 selected global climate models (shown in dark blue) by training with two observational datasets (Livneh for LOCA2 and nClimGrid for STAR; shown in green). The resulting algorithms produce high-resolution bias-adjusted datasets of daily temperature and precipitation for the training dataset observational period. These model-specific algorithms are applied to global projections to produce high-resolution projections of temperature and precipitation in the United States for each model (shown in light blue). The individual model projections are averaged with model weights based on climate sensitivity to produce the final NCA5 datasets and graphics. LOCA2 and STAR provide gridded data for the 48 contiguous states. STAR additionally includes downscaled data for individual stations in Alaska, Hawai'i, and Puerto Rico. Figure credit: USGCRP/ICF, USGCRP, and North Carolina State University.

# A3.3. Sea Level Rise

NCA5 authors were provided with sea level rise scenarios produced by an Interagency Task Force for the 2022 Sea Level Rise Technical Report.[28] The technical report uses five SLR scenarios covering the time period from 2020 to 2150, constructed using the sea level projections from the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6)[29] and defined by global mean SLR target values in 2100 as follows: Low (0.3 m [1 foot]), Intermediate-Low (0.5 m [1.5 feet]), Intermediate (1 m [3 feet]), Intermediate-High (1.5 m [5 feet]), and High (2 m [6.5 feet]). Specifically, the AR6 projections across all possible warming levels and emissions are filtered to find ones that describe pathways that meet these five target values of global mean sea level rise. Near-term SLR estimates are derived from an extrapolation of observed rates and acceleration through 2050.

These five SLR scenarios are related to, but distinct from, the CMIP6 temperature and precipitation projections described above in Sections A3.1 and A3.2. Describing these five scenarios reduces the complexity of sea level projections that are conditional on future emissions and difficult-to-quantify physical processes. This supports decision-making in a number of ways, including providing a risk-based framing and allowing planners to compare the performance of different management strategies over time under different SLR scenarios. Chapter 2 introduces these five scenarios; Chapter 9 uses these scenarios and the IPCC projections to provide details about sea level rise dynamics and regional sea level rise.

While it is not possible to directly assign probabilities to each of the scenarios, additional assumptions about the future (e.g., global warming level above preindustrial conditions; see the Guide to the Report) allow for the assignment of a probability of exceeding a particular sea level scenario in that assumed future (Table A3.1). Although generated using global mean SLR, these exceedance probabilities are applicable to the US due to the construction of the sea level projections. At 2100 and beyond, the primary driver of the upper end of the SLR scenarios is the potential for rapid ice sheet loss; to account for this possibility, the far-right column of Table A3.1 represents a future with very high emissions, high warming, and significant contributions to SLR from these ice loss processes.

**Table A3.1. Sea Level Rise Exceedance Probabilities**

The table shows the probabilities of exceeding the amounts of sea level rise (SLR) projected for the five scenarios (Low, Intermediate-Low, Intermediate, Intermediate-High, and High) provided in the 2022 Sea Level Rise Technical Report. Probabilities are shown for the end of the century (2100) for five global warming levels (calculated as global mean surface temperature increases above preindustrial levels for the period 2081–2100) as well as for a possible future with very high emissions and rapid ice sheet loss processes, which are currently understood with only *low confidence*. The probabilities are based on IPCC projections. Adapted from Sweet et al. 2022.[28]

| Probability of exceeding the SLR scenario described below in 2100 at the global warming level described to the right | 1.5°C (2.7°F) | 2.0°C (3.6°F) | 3.0°C (5.4°F) | 4.0°C (7.2°F) | 5.0°C (9°F) | *Low Confidence* ice sheet loss processes, very high emissions |
|---|---|---|---|---|---|---|
| **Low (0.3 m)** | 92% | 98% | >99% | >99% | >99% | >99% |
| **Intermediate-Low (0.5 m)** | 37% | 50% | 82% | 97% | >99% | 96% |
| **Intermediate (1.0 m)** | <1% | 2% | 5% | 10% | 23% | 49% |
| **Intermediate-High (1.5 m)** | <1% | <1% | <1% | 1% | 2% | 20% |
| **High (2.0 m)** | <1% | <1% | <1% | <1% | <1% | 8% |

# A3.4. Tools and Applications

In addition to projections, the TSU developed historical climate information for NCA5 authors. Historical analyses are based on NOAA's nClimGrid and GHCN-Daily datasets,[30] and access was provided via an interactive visualization tool. Historical and projected climate variables from the TSU analysis include average annual and seasonal temperature and precipitation, extreme maximum and minimum quantities, threshold exceedances, and derived variables such as mean summer soil moisture and minimum annual temperature. The full suite of historical and future climate data and metadata records developed for NCA5 will be made publicly available via the NCA5 Atlas and through the Global Change Information System. The NCA5 Indicators Appendix provides more detail on observed trends for commonly used climate metrics (App. 4).

# References


1. IPCC, 2021: Annex VII: Glossary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, S. Semenov, and A. Reisinger, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2215–2256. https://doi.org/10.1017/9781009157896.022

2. O'Neill, B.C., E. Kriegler, K. Riahi, K.L. Ebi, S. Hallegatte, T.R. Carter, R. Mathur, and D.P. van Vuuren, 2014: A new scenario framework for climate change research: The concept of Shared Socioeconomic Pathways. *Climatic Change*, **122** (3), 387–400. https://doi.org/10.1007/s10584-013-0905-2

3. Riahi, K., D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J.C. Cuaresma, S. Kc, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J.C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, and M. Tavoni, 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

4. van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, and S.K. Rose, 2011: The Representative Concentration Pathways: An overview. *Climatic Change*, **109** (1), 5. https://doi.org/10.1007/s10584-011-0148-z

5. Tebaldi, C., K. Debeire, V. Eyring, E. Fischer, J. Fyfe, P. Friedlingstein, R. Knutti, J. Lowe, B. O'Neill, B. Sanderson, D. van Vuuren, K. Riahi, M. Meinshausen, Z. Nicholls, K.B. Tokarska, G. Hurtt, E. Kriegler, J.F. Lamarque, G. Meehl, R. Moss, S.E. Bauer, O. Boucher, V. Brovkin, Y.H. Byun, M. Dix, S. Gualdi, H. Guo, J.G. John, S. Kharin, Y. Kim, T. Koshiro, L. Ma, D. Olivié, S. Panickal, F. Qiao, X. Rong, N. Rosenbloom, M. Schupfner, R. Séférian, A. Sellar, T. Semmler, X. Shi, Z. Song, C. Steger, R. Stouffer, N. Swart, K. Tachiiri, Q. Tang, H. Tatebe, A. Voldoire, E. Volodin, K. Wyser, X. Xin, S. Yang, Y. Yu, and T. Ziehn, 2021: Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth System Dynamics*, **12** (1), 253–293. https://doi.org/10.5194/esd-12-253-2021

6. Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T.Y. Jung, T. Kram, E. Lebre La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi, 2000: *IPCC Special Report on Emissions Scenarios*. Nakicenovic, N. and R. Swart, Eds. Cambridge University Press, Cambridge, UK, 599 pp. http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0

7. Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Appendix 3: Climate science supplement. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T. (T.C.) Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 735–789. https://doi.org/10.7930/j0ks6phh

8. Hayhoe, K., J. Edmonds, R.E. Kopp, A.N. LeGrande, B.M. Sanderson, M.F. Wehner, and D.J. Wuebbles, 2017: Ch. 4. Climate models, scenarios, and projections. In: *Climate Science Special Report: Fourth National Climate Assessment*, Volume I. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 133–160. https://doi.org/10.7930/j0wh2n54

9. Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld, 2021: Technical summary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 33–144. https://doi.org/10.1017/9781009157896.002

10. Eyring, V., S. Bony, G.A. Meehl, C.A. Senior, B. Stevens, R.J. Stouffer, and K.E. Taylor, 2016: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, **9** (5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

11. Meehl, G.A., C.A. Senior, V. Eyring, G. Flato, J.-F. Lamarque, R.J. Stouffer, K.E. Taylor, and M. Schlund, 2020: Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. *Science Advances*, **6** (26), 1981. https://doi.org/10.1126/sciadv.aba1981

12. Nijsse, F.J.M.M., P.M. Cox, and M.S. Williamson, 2020: Emergent constraints on transient climate response (TCR) and equilibrium climate sensitivity (ECS) from historical warming in CMIP5 and CMIP6 models. *Earth System Dynamics*, **11** (3), 737–750. https://doi.org/10.5194/esd-11-737-2020

13. Brunner, L., A.G. Pendergrass, F. Lehner, A.L. Merrifield, R. Lorenz, and R. Knutti, 2020: Reduced global warming from CMIP6 projections when weighting models by performance and independence. *Earth System Dynamics*, **11** (4), 995–1012. https://doi.org/10.5194/esd-11-995-2020

14. Hausfather, Z., K. Marvel, G.A. Schmidt, J.W. Nielsen-Gammon, and M. Zelinka, 2022: Climate simulations: Recognize the 'hot model' problem. *Nature*, **605** (7908), 26–29. https://doi.org/10.1038/d41586-022-01192-2

15. Global Change Research Act of 1990. 101st Congress, Pub. L. No. 101-606, 104 Stat. 3096–3104, November 16, 1990. https://www.congress.gov/bill/101st-congress/senate-bill/169/text

16. Meinshausen, M., Z.R.J. Nicholls, J. Lewis, M.J. Gidden, E. Vogel, M. Freund, U. Beyerle, C. Gessner, A. Nauels, N. Bauer, J.G. Canadell, J.S. Daniel, A. John, P.B. Krummel, G. Luderer, N. Meinshausen, S.A. Montzka, P.J. Rayner, S. Reimann, S.J. Smith, M. van den Berg, G.J.M. Velders, M.K. Vollmer, and R.H.J. Wang, 2020: The Shared Socio-economic Pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, **13** (8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

17. Sarofim, M.C., J. Martinich, J.E. Neumann, J. Willwerth, Z. Kerrich, M. Kolian, C. Fant, and C. Hartin, 2021: A temperature binning approach for multi-sector climate impact analysis. *Climatic Change*, **165** (1), 22. https://doi.org/10.1007/s10584-021-03048-6

18. Tebaldi, C. and R. Knutti, 2018: Evaluating the accuracy of climate change pattern emulation for low warming targets. *Environmental Research Letters*, **13** (5), 055006. https://doi.org/10.1088/1748-9326/aabef2

19. Pierce, D.W., D.R. Cayan, D.R. Feldman, and M.D. Risser, 2023: Future increases in North American extreme precipitation in CMIP6 downscaled with LOCA. *Journal of Hydrometeorology*, **24**, 951–975. https://doi.org/10.1175/jhm-d-22-0194.1

20. Hayhoe, K., A. Stoner, D.J. Wuebbles, and I. Scott-Fleming, 2023: STAR-ESDM: A generalizable approach to generating high-resolution climate projections through signal decomposition. *ESS Open Archive*. https://doi.org/10.22541/essoar.169462036.65393270/v1

21. Hayhoe, K., A.M. Stoner, I. Scott-Fleming, and H. Ibrahim, 2021: STAR-ESDM: A new bias correction method for high-resolution station- and grid-based climate projections. In: *EGU General Assembly Conference Abstracts*. 19–30 April 2021, EGU21-13931. https://doi.org/10.5194/egusphere-egu21-13931

22. Massoud, E.C., H. Lee, P.B. Gibson, P. Loikith, and D.E. Waliser, 2020: Bayesian model averaging of climate model projections constrained by precipitation observations over the contiguous United States. *Journal of Hydrometeorology*, **21** (10), 2401–2418. https://doi.org/10.1175/jhm-d-19-0258.1

23. Wootten, A.M., E.C. Massoud, A. Sengupta, D.E. Waliser, and H. Lee, 2020: The effect of statistical downscaling on the weighting of multi-model ensembles of precipitation. *Climate*, **8** (12), 138. https://doi.org/10.3390/cli8120138

24. Wootten, A.M., E.C. Massoud, D.E. Waliser, and H. Lee, 2023: Assessing sensitivities of climate model weighting to multiple methods, variables, and domains in the south-central United States. *Earth System Dynamics*, **14** (1), 121–145. https://doi.org/10.5194/esd-14-121-2023

25. Massoud, E., K. Lee, A. Terando, and M. Wehner, 2023: Bayesian weighting of climate models based on climate sensitivity. *Communications Earth and Environment*. https://doi.org/10.1038/s43247-023-01009-8

26. Bukovsky, M.S. and L.O. Mearns, 2020: Regional climate change projections from NA-CORDEX and their relation to climate sensitivity. *Climatic Change*, **162** (2), 645–665. https://doi.org/10.1007/s10584-020-02835-x

27. Giorgi, F., C. Jones, and G.R. Asrar, 2009: Addressing climate information needs at the regional level: The CORDEX framework. *WMO Bulletin*, **58** (3), 175–183. https://public.wmo.int/en/bulletin/addressing-climate-information-needs-regional-level-cordex-framework

28. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

29. Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ch. 9. Ocean, cryosphere and sea level change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1211–1362. https://doi.org/10.1017/9781009157896.011

30. Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams Jr., C. Fenimore, K. Gleason, and D. Arndt. 2014: NOAA Monthly U.S. Climate Gridded Dataset (NClimGrid), Version 1. National Oceanic and Atmospheric Administration, National Centers for Environmental Information. https://doi.org/10.7289/v5sx6b56

Fifth National Climate Assessment: Appendix 4

# Indicators

# Appendix 4. Indicators

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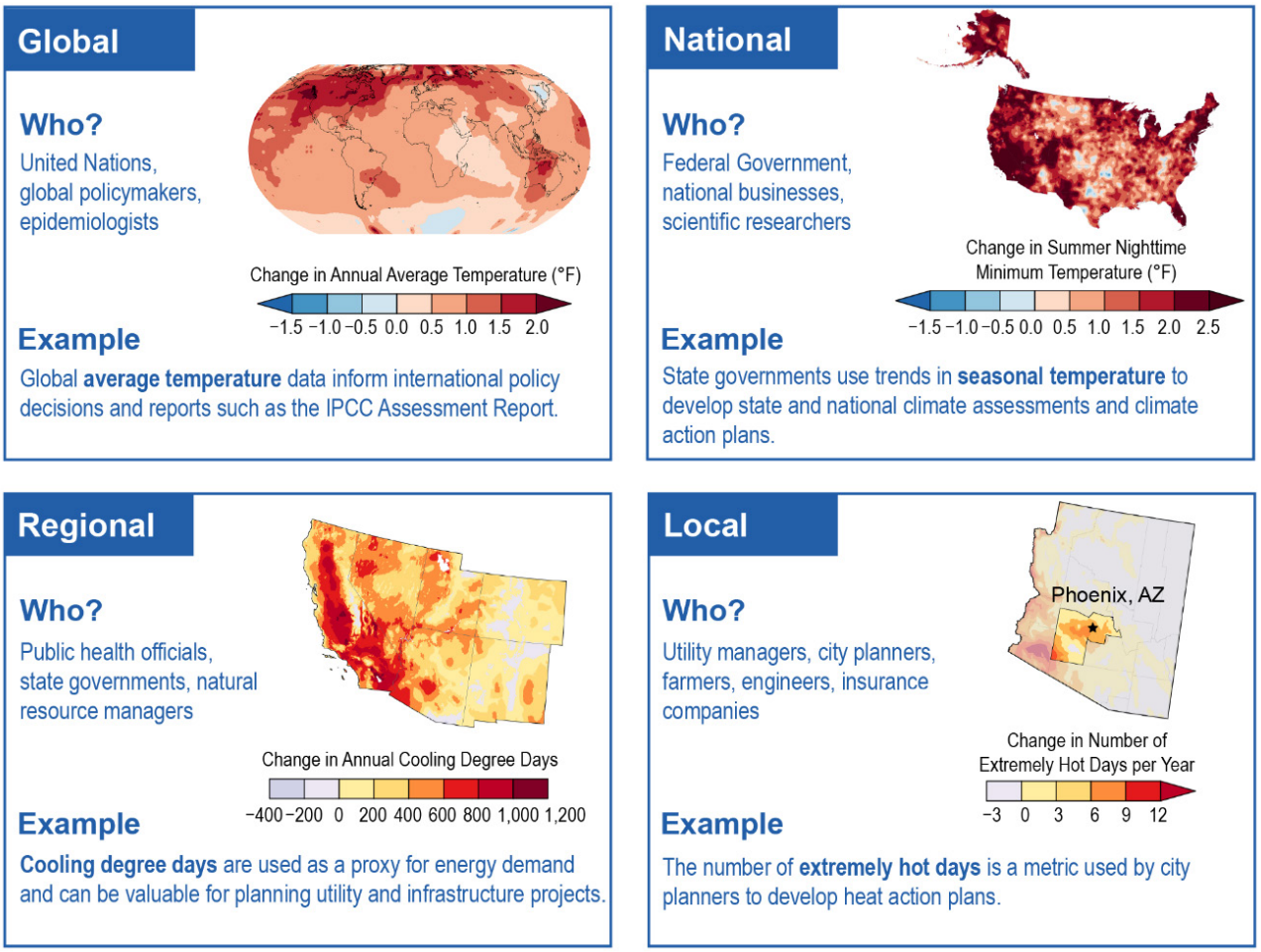
# A4.1. The Importance of Indicators

To evaluate the impacts of climate change, it is essential to first understand the many ways in which our climate is changing. Indicators characterize how environmental conditions are changing over time to help communicate climate impacts, risks, and vulnerabilities. Indicators provide foundational science in support of the US Global Change Research Program's (USGCRP) sustained assessment process, including the National Climate Assessment (NCA). In the NCA, indicators are defined as data (presented as charts or maps) based on historical observations and measurements that are used to track conditions, trends, and impacts related to our changing climate. Indicators show changes in physical, ecological, or societal systems and can represent data at varying scales, from global to local (Figure A4.1). Indicators are of most value when maintained and updated on a regular basis so that users and stakeholders can make informed decisions based on the most up-to-date information. Taken individually, each indicator depicts a specific change over time, while a broad set of indicators helps to show interconnections among the many components of global change and a warming world (Box A4.1).[1] While each indicator has an important relationship to climate,[2] it is beyond the scope of this appendix to explore these connections in detail. Attribution and causation related to a changing climate are discussed in other chapters throughout NCA5 (e.g., Chs., 2, 3, 15).

## Changes in Temperature at Multiple Scales




**Presenting indicators at different scales allows stakeholders to obtain information relevant to their needs.**

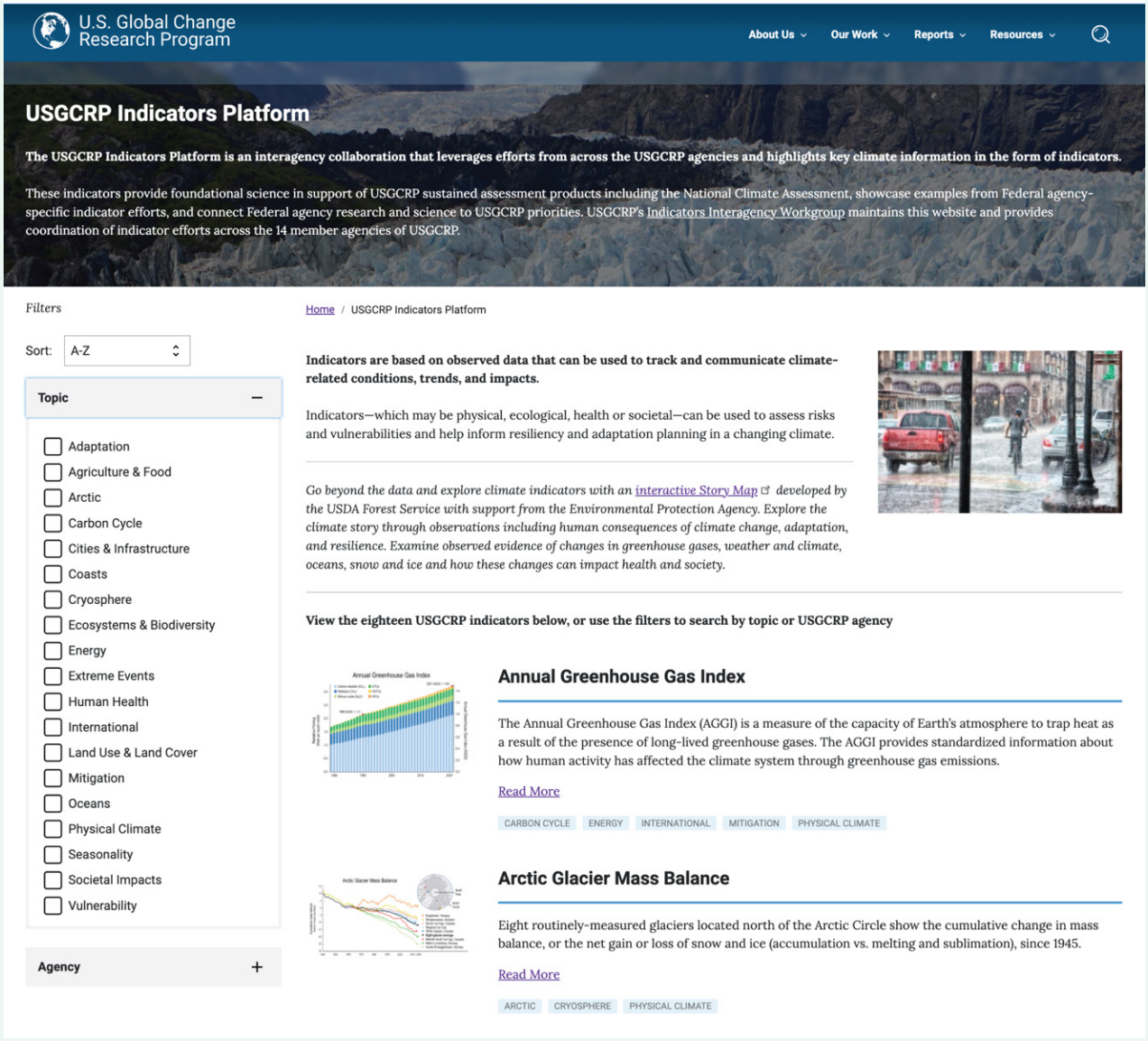
**Figure A4.1.** Many people use climate-related indicators for resource and management decisions, from small-scale farmers to global policymakers. Different indicators are relevant at different geographic scales, depending on who uses the information and for what purpose. In this figure, temperature indicators are shown at four scales, with each map depicting spatial patterns in the amount of observed change: (**top left**) global annual average temperature for the period 1993–2022, relative to 1901–1960; (**top right**) national (contiguous US and Alaska) summer nighttime minimum temperature for 1993–2022, relative to 1901–1960 (relative to 1926–1960 for Alaska; data are not available for the US Caribbean, Hawai'i, or the US-Affiliated Pacific Islands); (**bottom left**) regional (Southwest region) cooling degree days for 1993–2022, relative to 1951–1980; and (**bottom right**) local (Maricopa County, Arizona) number of days with maximum temperatures of 110°F or higher for 1993–2022, relative to 1951–1980. Data used for the regional and local indicators are available only from 1951 onwards. In general, increases in each metric have occurred since the start of their respective records, with important variations that are relevant to decision-makers at each scale (see Section A4.2 for additional explanation). Figure credit: North Carolina State University and NOAA NCEI.

Indicators are needed to support decision-making and describe and monitor impacts on people. Combined with other data, such as demographic and socioeconomic information (e.g., Figures A4.4, A4.14, 11.13), their utility is ever-growing, with many advancements being made in recent years (e.g., Di Napoli et al. 2022;[3] Kenney et al. 2020;[4] Walsh et al. 2020[5]). Indicators are being developed by USGCRP agencies (Box A4.1), their partners, academic institutions, and state, local, and Indigenous communities. The form, complexity, breadth, and design of indicators vary based on their intended uses, but effective indicators clearly convey information to advance understanding related to changes in key aspects of climate and the impacts on people and ecosystems. Measuring the health and societal effects of climate change is challenging because of the complex, often indirect relationships among climate drivers, environmental and social factors, and health outcomes.[6,7] Increasingly, physical, ecological, and socioeconomic data are being linked together to better track impacts on human systems, allowing communities to assess risks and make informed response and adaptation decisions. In the context of human health, identifying sets of indicators along exposure pathways can help track the related nature of exposures and the prevalence of health outcomes.[7,8] This holistic approach can provide insights into the extent to which changes in climate affect people and help identify opportunities for public health actions to reduce or prevent exposures and adverse health effects.

## Box A4.1. Federal Indicator Resources

The US Global Change Research Program (USGCRP) coordinates efforts to highlight climate-relevant indicators from across federal agencies. The USGCRP Indicators Interagency Working Group guides this effort through advancing the research, development, and integration of indicators into USGCRP activities and products and highlights a subset of these on the USGCRP Indicators Platform (Figure A4.2).[9] Indicators hosted on the platform consist of peer-reviewed observational data and methods from federal entities and are routinely updated. They meet the standards set forth by the Information Quality Act regarding data quality, transparency, and traceability (App. 2).

### USGCRP Indicators Platform




**The USGCRP Indicators Platform leverages agency-supported science and data to understand how environmental, health, and societal conditions are changing.**

**Figure A4.2.** Screenshot from the USGCRP Indicators Platform: https://www.globalchange.gov/indicators/. Figure credit: USGCRP 2023.[9]

Other federal climate-related indicators efforts include:

- CDC's National Environmental Public Health Tracking Climate Change Indicators[10]
- EPA's Climate Change Indicators in the United States[2]
- EPA's Climate Indicator Map Viewer[11]
- NASA's Vital Signs of the Planet[12]
- NOAA's National Marine Ecosystems Indicators[13]
- NOAA's State Climate Summaries[14]
- USDA's Climate Indicators for Agriculture[5]

Indicators appear in every NCA, with each report offering new ways to evaluate observed changes. This appendix marks the first time a section of the NCA has been established to present and discuss nationally relevant indicators. It highlights the important role of indicators and supports the NCA with scientific evidence, using a representative set of indicators relevant to multiple chapters. Observed changes relevant to each regional chapter can be represented with indicators, as shown in Table A4.1. Indicators in this appendix are grouped into six categories (Atmosphere; Ice, Snow and Water; Ocean and Coastal; Land and Ecosystems; Health; Adaptation and Mitigation), building on NCA4's Indicators of Change figure (Figure 1.2 in Jay et al. 2018[1]). Examples for each category were selected to cover a diverse range of regions, highlight both existing and newly developed indicators, and focus on topics relevant to urban and rural populations as well as the natural environment. These and many other indicators in NCA5 demonstrate that climate change is happening now (Table A4.1; KM 2.1; Figures 28.1, 30.5).

## Table A4.1. Observed Regional Changes

This table shows observed changes pertinent to each NCA region, along with supporting evidence from associated NCA5 Key Messages and example indicators. The observed changes are only selected examples and do not necessarily convey which climate-related risks are most significant in each area. See the regional chapters for more detail on these observed changes and related climate impacts.

| Region | Observed Change | Key Message | Example Indicator(s) |
|---|---|---|---|
| Northeast | Increasing frequency and intensity of precipitation | KM 21.2 | Figure 2.8, Figure 21.1 |
| | Increasing ocean temperatures | KM 21.2 | Figure A4.11, Figure 21.4 |
| | Rising sea levels | KM 21.2 | Figure A4.10, Figure 2.5 |
| Southeast | Increasing frequency, intensity, and duration of heatwaves | KM 22.2 | |
| | Increasing wildfire risk | KM 22.2 | Figure A4.14 |
| | Rising sea levels | KM 21.4 | Figure 2.5 |
| US Caribbean | Increasing air temperatures | Ch. 23, Intro | Figure 1.5 |
| | Increasing ocean temperatures | Ch. 23, Intro | Figure A4.11 |
| | Increasing air pollution | KM 23.1 | |
| Midwest | Increasingly variable precipitation | KM 24.1 | Figure 2.4, Figure 2.8 |
| | Lengthening growing season | KM 24.1 | Figure 24.3 |
| | Changing Great Lakes water quantity, quality, and temperature | KM 24.5 | Figure 24.13 |
| Northern Great Plains | Increasing winter temperatures | KM 25.1 | Figure 2.4 |
| | Increasing wildfire risk | KM 25.1 | Figure A4.14 |
| | Increasing frequency of spring flood events | KM 25.1 | |

| Region | Observed Change | Key Message | Example Indicator(s) |
|---|---|---|---|
| Southern Great Plains | Increasing frequency and intensity of precipitation | Ch. 26, Intro | Figure 2.8, Figure 26.1 |
| | Increasing ocean temperatures | KM 26.3 | Figure A4.11 |
| | Rising sea levels | KM 26.5 | Figure 2.5 |
| Northwest | Declining snowpack | Ch. 27, Intro | Figure A4.7 |
| | Melting glaciers | Ch. 27, Intro | |
| | Rising sea levels | Ch. 27, Intro | Figure 2.5 |
| Southwest | Declining flows in major rivers | KM 28.1 | Figure 4.18, Figure 7.9 |
| | Increasing wildfire risk | KM 28.5 | Figure A4.14 |
| | Increasing number of marine heatwaves | KM 28.2 | Figure A4.11, Figure 28.4 |
| Alaska | Thawing permafrost | Ch. 29, Intro | |
| | Increasing ocean temperatures | Ch. 29, Intro | Figure A4.11 |
| | Declining sea ice | Ch. 29, Intro | Figure A4.6, Figure 2.3 |
| Hawai‘i and the US-Affiliated Pacific Islands | Increasing drought frequency, severity, and duration | Ch. 30, Intro | |
| | Increasing tropical cyclone activity | KM 30.2 | |
| | Rising sea levels | KM 30.3 | Figure 2.5 |

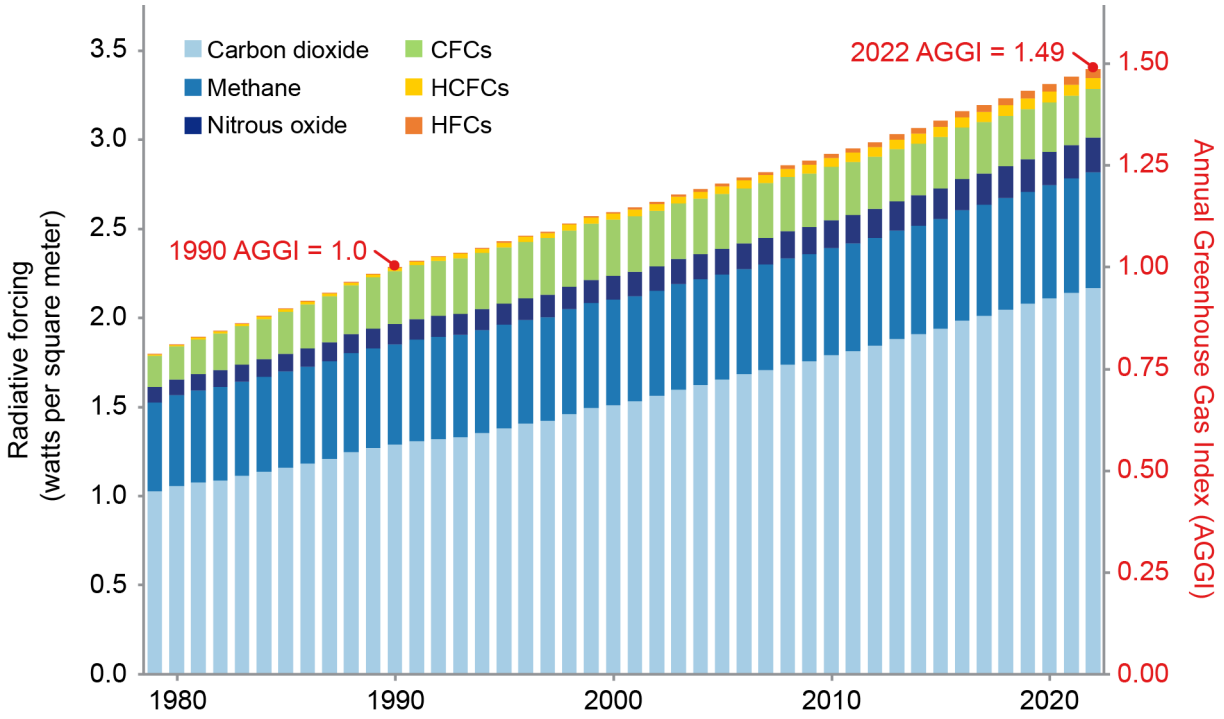
# A4.2. Atmospheric Indicators

Both globally and across the US, temperatures are rising as a result of increasing greenhouse gases (GHGs) in our atmosphere (Figures 1.5, 2.4), primarily caused by human activities (Figures 2.1, 3.1; KMs 2.1, 3.1). Extreme events such as heatwaves, heavy downpours, and severe flooding are also increasing in frequency and intensity (KM 2.2; Figures 2.8, 21.1, A4.8). Atmospheric indicators are used to inform decision-making across a wide variety of scales (Figure A4.1) and often form the basis for assessing trends, impacts, and key risks[15] among all sectors.

## *Greenhouse Gases*

Greenhouse gas emissions are the primary driver of climate change (KMs 2.1, 3.1), so tracking emissions is fundamental to understanding and responding to climate change. Figure 2.1 depicts the continual increase in carbon dioxide ($CO_2$) emissions by the greatest contributing countries and regions. The Annual Greenhouse Gas Index indicator (Figure A4.3) accounts for global emissions of $CO_2$ and the other major long-lived greenhouse gases from 1979 to 2022 and shows how the cumulative warming effects of these GHGs have been increasing over time.

### Annual Greenhouse Gas Index




**The warming effects of greenhouse gases are increasing over time.**

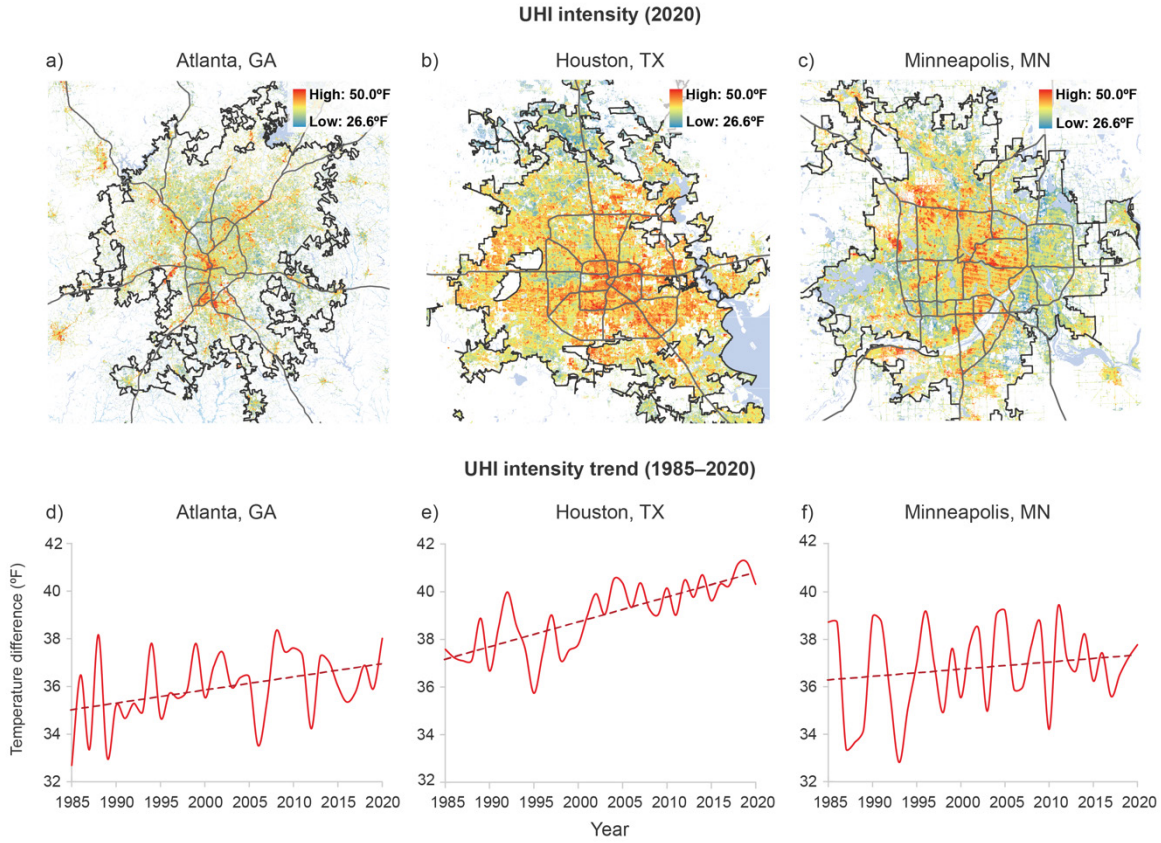
**Figure A4.3.** Radiative forcing (left vertical axis) is the change, either positive or negative, in the amount of energy from the sun that is trapped by Earth's atmosphere. Increases in the amount of radiative forcing will lead to warming. The Annual Greenhouse Gas Index (AGGI; right vertical axis) compares the total radiative forcing for each year from 1979 to 2022 to the year 1990 (represented by a red dot). The year 1990 was selected as the year for comparison because that is the year the Montreal Protocol[16] was signed, so its AGGI value is designated here as 1.0. The 2022 AGGI (also represented by a red dot) was 1.49, indicating that the average warming influence of long-lived greenhouse gases in the atmosphere has increased by a total of 49% since 1990. The increased radiative forcing leads to increasing temperatures, both in the oceans and over land. Indicators of these changes and impacts are found in this appendix and throughout the report. CFCs = chlorofluorocarbons, HFCs = hydrofluorocarbons, HCFCs = hydrochlorofluorocarbons. Adapted from USGCRP 2023.[17]

## *Temperature and Extreme Heat*

Long-term observations show that warming due to climate change is unambiguous but is not occurring equally or in all areas (Figures A4.1, 2.4, 2.7). Figure A4.1 shows four different temperature indicators valuable to decision-makers at multiple scales. Globally, annual average temperatures have increased almost everywhere, with the greatest increases seen across North America and the Arctic (Figure A4.1, top left). On the national scale, nights have been warming faster than days (KM 2.2), with the greatest increases in summer nighttime minimum temperatures seen across large areas of Alaska, Florida, and the western and northeastern United States (Figure A4.1, top right). On the regional scale, cooling degree days (a proxy for energy demand used to cool buildings) have increased throughout the Southwest, with California experiencing the greatest changes (Figure A4.1, bottom left). And on a local level, the number of days per year with temperatures reaching 110°F or more have increased throughout Maricopa County, Arizona, with the Phoenix area experiencing notable increases in these extremely hot days (Figure A4.1, bottom right). Additionally, in the United States, the rate at which temperatures increase differs seasonally (Figure 2.4).[18] Changes in seasonal temperatures have led to shifts in the seasonality of certain events (Figure A4.13). In some areas, the combination of high humidity and high temperatures is contributing to the emergence of heat index values too severe for human tolerance (KM 2.3).[19,20] As temperatures increase, people's exposure to extreme heat becomes greater (KMs 3.12, 15.1).

These increasing temperatures directly and indirectly impact human health and societal outcomes (KM 2.2; Ch. 15). Populations directly exposed to more heatwaves experience increased heat-related illness and death.[21,22] Since the 1960s, the frequency of heatwaves and the duration of heatwave seasons have steadily increased in certain areas (KM 2.2).[23] Urban areas experience higher temperatures than surrounding landscapes because many structures such as roads and buildings absorb and radiate heat, exacerbating the effects of increasing temperatures (Figure A4.4; KM 12.1). Additionally, changes in land use in and around urban areas have contributed to temperature hotspots (Figure 6.3).

## Urban Heat Island (UHI) Intensity




**Urban heat island intensity is increasing in many US cities due to the combination of urbanization and rising temperatures.**

**Figure A4.4.** Urban heat island (UHI) intensity is defined as the annual difference in average temperature between areas that are urban versus nonurban (within a 5 km, or approximately 3.1-mile, buffer zone of the city boundary). Indicators and maps of UHI intensity can help inform heat-mitigation strategies such as implementing urban vegetation cover.[24] Top row: Maps for the year 2020 are presented for (**a**) Atlanta, (**b**) Houston, and (**c**) Minneapolis, showing temperature differences used to determine UHI intensity for that year. Both hotspots and areas of lower temperatures are evident. Bottom row: Trends in average UHI intensity from 1985 to 2020 are presented for (**d**) Atlanta, (**e**) Houston, and (**f**) Minneapolis. Solid lines show observed data, while dashed lines represent the estimated trend for the period of record. Companion figures depicting the relationship between temperature and socioeconomic factors for these same cities can be seen in Figure 12.6. Figure credits: (a, c, d, f) adapted from Xian et al. 2022;[24] (b, e) USGS and NIEHS / Kelly Government Solutions.

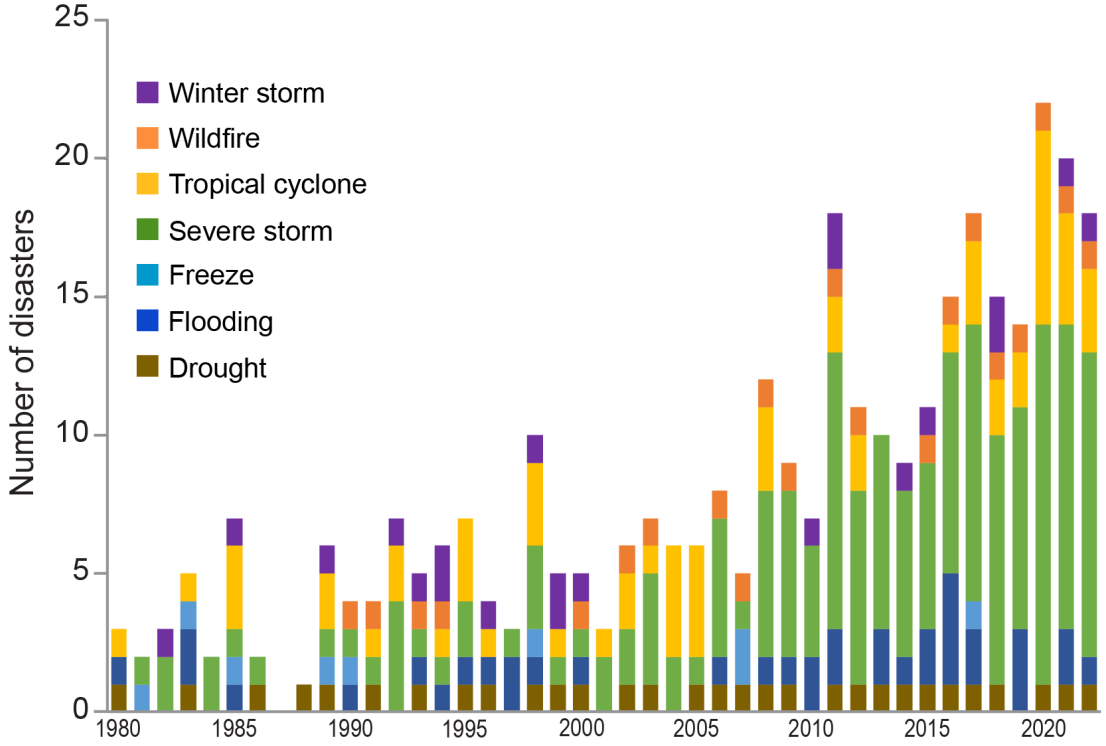
## *Precipitation*

As temperatures rise, US precipitation patterns are changing, with long-term trends in average precipitation differing considerably by region and by season (Figure 2.4).[14] Indicators can show how changes in these patterns may affect different sectors. For example, too much or too little precipitation can impact both crop (KM 4.1) and hydropower (KM 5.1) production. Seasonal activities of sensitive plant and animal species may shift as precipitation amounts and timing change (Figure 8.11). Indicators can also be used to observe how heavy precipitation events are evolving in intensity (e.g., Figure 2.8), frequency (e.g., Kunkel et al. 2022[14]), and duration (e.g., Kunkel et al. 2020[25]). For example, evidence suggests that in recent years, extreme single-day precipitation events are increasing in the United States.[26] Heavy precipitation will become increasingly important to local engineering and community planning as the risk of flooding increases in a warmer world;[25] as a result, regional- and local-scale indicators are most valuable for informing adaptive actions to protect public health and safety.

## *Extreme Events*

Climate change is increasing the frequency and severity of many extreme weather and climate events (Figure 1.7; KM 2.2), including heatwaves,[23] heavy precipitation (Figure 2.8; KMs 4.1, 21.1; KM 22.1), drought (Section A4.3), flooding (Section A4.3; KM 4.1), wildfire (Section A4.5; KM 7.1; Focus on Western Wildfires), and tropical cyclones (KM 2.2).[27] Other events, such as cold snaps, are becoming less frequent (KM 2.2). Extreme-event indicators allow communities to evaluate changes in risk, as major weather and climate disasters can threaten lives, damage property, and affect daily activities. One example is the number of disasters in the US each year that cause at least $1 billion in damages (Figures A4.5, 1.7, 2.6, 22.3). More frequent and compound extreme events (Focus on Compound Events) disproportionately impact already-overburdened groups (KM 18.2; Box 18.2), leaving communities with less time and fewer resources to respond to each disaster.

### Billion-Dollar Disasters




**The number of weather- and climate-related disasters exceeding $1 billion has substantially increased since 1980.**

**Figure A4.5.** This indicator provides insight into the frequency of events exceeding $1 billion in damages (adjusted for inflation) from 1980 to 2022 across seven disaster types, each represented by its own color. The severe storm category includes events such as tornadoes, hail, and damaging winds but not tropical cyclones or winter storms. The only year with no billion-dollar events was 1987. Since then, the number of events each year has generally increased, with 2020 and 2021 having the two highest number of events on record. The number and cost of these disasters are due to several complex factors. Climate change is leading to increases in the frequency and intensity of extreme events, and, at the same time, there have been continual increases in the numbers of buildings, infrastructure, and people in climate-sensitive areas where these events may occur.[28] Economic factors can also play a role. For example, there is potential for property values to increase at rates higher than the Consumer Price Index, which can lead to higher damage assessments compared to previous years. An interactive version of this indicator, including the total annual cost and a breakdown by state and region, can be found at https://www.ncei.noaa.gov/access/billions/time-series/.[29] Adapted from USGCRP 2023.[30]

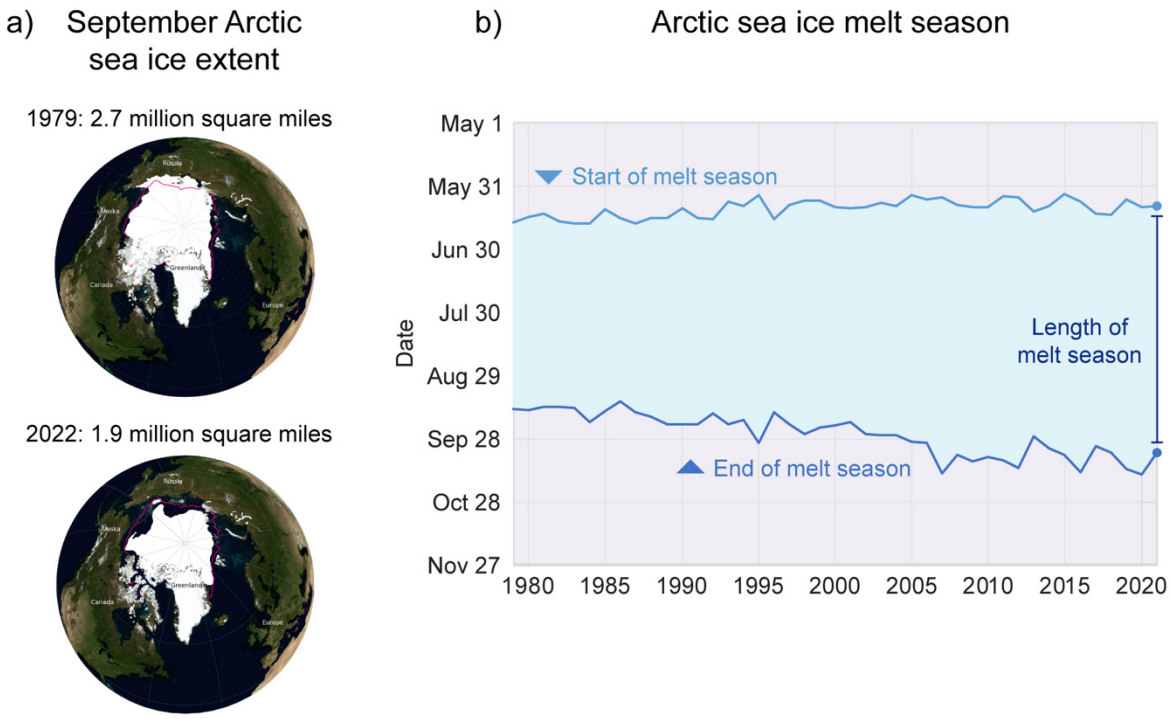
# A4.3. Ice, Snow, and Water Indicators

Many parts of the US are experiencing intensified droughts or reduced snowpack, which are caused or exacerbated by rising temperatures (KMs 2.2, 4.1). These changes, combined with increasing water demand from growing populations, can reduce the reliability of water supplies,[31,32] and water-related indicators can help communities prepare for impacts. Also useful are indicators used to track changes in the cryosphere (the frozen parts of Earth's surface), as melting sea and land ice (e.g., ice sheets and glaciers) and thawing permafrost can contribute to sea level rise (KM 9.1; Figures 2.5, 9.1), affect water supply (KM 4.1), and have other negative impacts on humans and ecosystems (KM 8.2; Ch. 29).

## *Sea Ice*

Changes in Arctic sea ice are some of the most visible and well-known indicators of a changing climate.[33,34,35] The steep decline of average Arctic sea ice extent in September, when the ice shrinks to its smallest area each year, is shown in Figure 2.3. Figure A4.6 illustrates how the total area of September sea ice has declined and how the overall length of the melt season is increasing over time. Melt location and timing is important, because as sea ice melts, it changes ocean and atmospheric circulation patterns, which can impact marine life and coastal economies (KM 10.1). Additionally, loss of sea ice is leading to increases in commercial shipping; exploration of oil, gas, and minerals; and geopolitical and global security issues (Ch. 17; KM 29.6).[36]

### Changes in Arctic Sea Ice



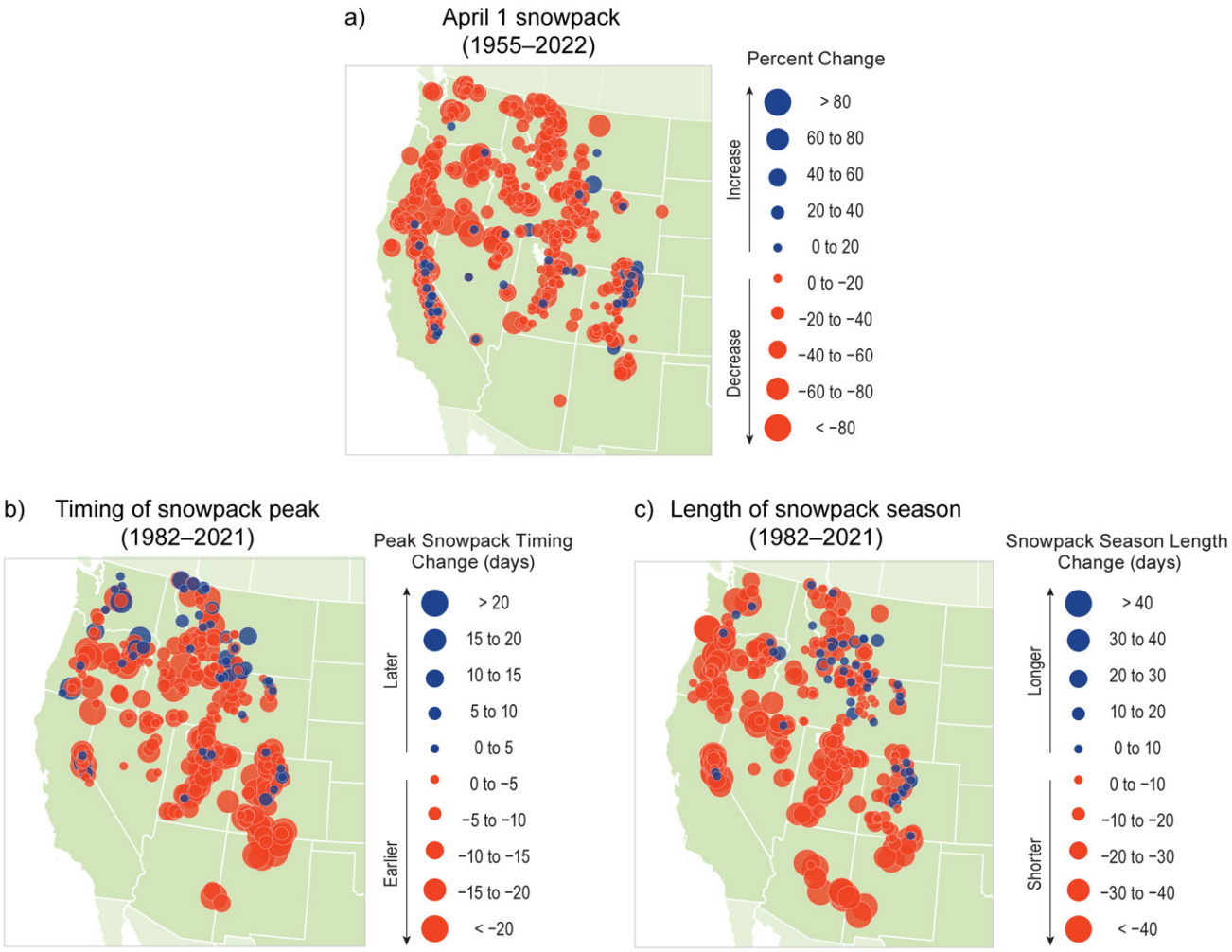

**Arctic sea ice is shrinking as the melt season grows longer.**

**Figure A4.6.** An increasingly later end to the melt season is the primary contributor to both the longer season and the declining ice extent. (**a**) This indicator compares the annual minimum sea ice extent—the smallest area of sea ice—measured in the Arctic in 1979 (the beginning of the record) and 2022 (the most recent year of observation). The pink line on each map represents the median ice edge for 1981 to 2010. (**b**) This indicator shows the annual length of the Arctic sea ice melt season from 1979 to 2021. The blue shaded area represents the amount of time between the date when ice begins to melt consistently (light blue line) and the date when it begins to refreeze (dark blue line). (a) Adapted from NSIDC 2023;[37] imagery from the Special Sensor Microwave Imager/Sounder (SSMIS) instrument, courtesy of NASA and NSIDC; (b) adapted from EPA 2023.[33]

## *Snowpack and Snow Cover*

As US winters and springs warm, the amount and seasonality of snow is changing (KM 2.2). Higher temperatures cause snow to melt earlier, which affects timing and availability of water (KM 2.2).[38] A variety of indicators can be used to track changes in snowpack and snow cover (Figure A4.7). These indicators focus on the western US, where millions of people depend on the melting of mountain snowpack for drinking water, crop irrigation, and hydropower (Ch. 4; KM 28.1). Changes in snowpack and snow cover affect winter recreation, tourism, plants, and wildlife.[38]

### Snowpack Changes in the West



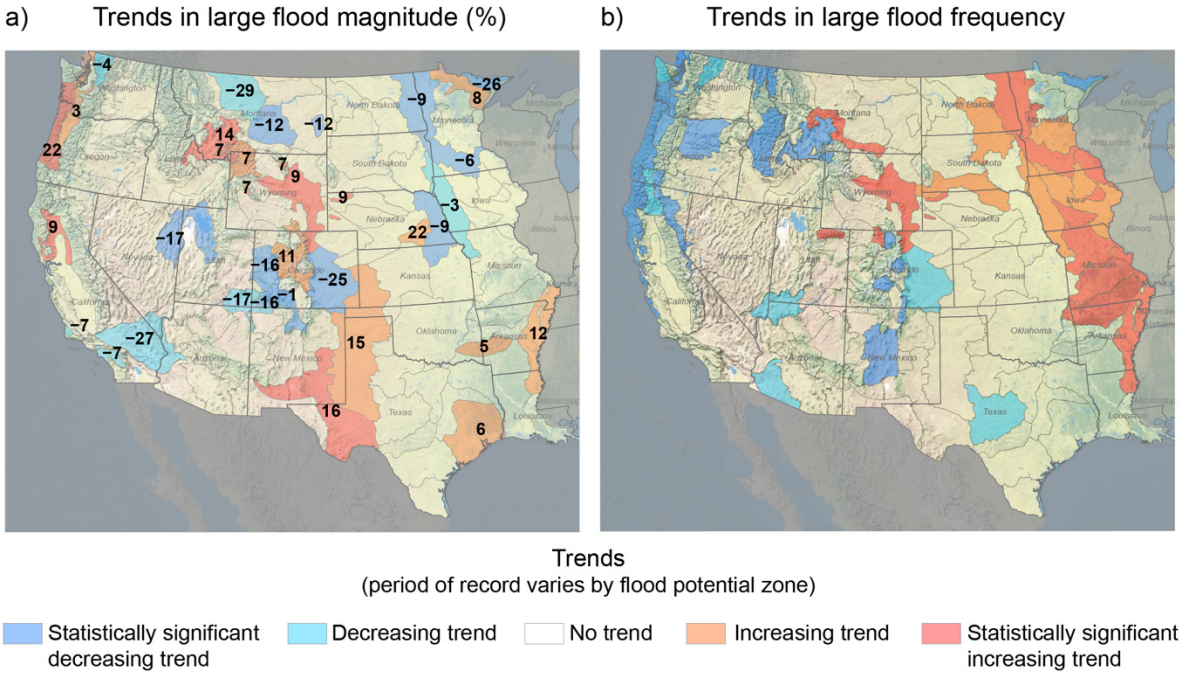

**Western snowpack is declining, peak snowpack is occurring earlier, and the snowpack season is shortening in length.**

**Figure A4.7.** The overall amount of snow has been declining across the western United States, as shown in three indicators: (**a**) trends in snowpack on April 1 (percent change) from 1955 to 2022 (red and blue circles represent a decrease and increase, respectively); (**b**) change in the annual date when snowpack reaches its maximum amount (days) from 1982 to 2021 (red and blue circles represent a shift to earlier and later timing, respectively); and (**c**) change in snowpack season length (days) from 1982 to 2021 (red and blue circles represent a shortening and lengthening of the snowpack season, respectively). Adapted from EPA 2023.[38]

## *Flooding*

Indicators can be used to quantify trends in large floods, which is imperative for floodplain management and infrastructure design to maximize safety and resilience (KMs 4.2, 6.1, 12.4). For example, west of the Mississippi River, nearly 30% of monitored areas are experiencing increases in large flood frequency and/or magnitude (Figure A4.8). In contrast, other areas have recently experienced decreasing trends due to prevailing climate patterns such as the Southwest megadrought (KM 28.1).[39] Flood indicators are also used to track economic damage related to flooding (Figure 4.12) and monitor flood trends of individual streams.[40]

### Flood Frequency and Magnitude West of the Mississippi River




**Trends in flood magnitude and frequency vary widely across the western US.**

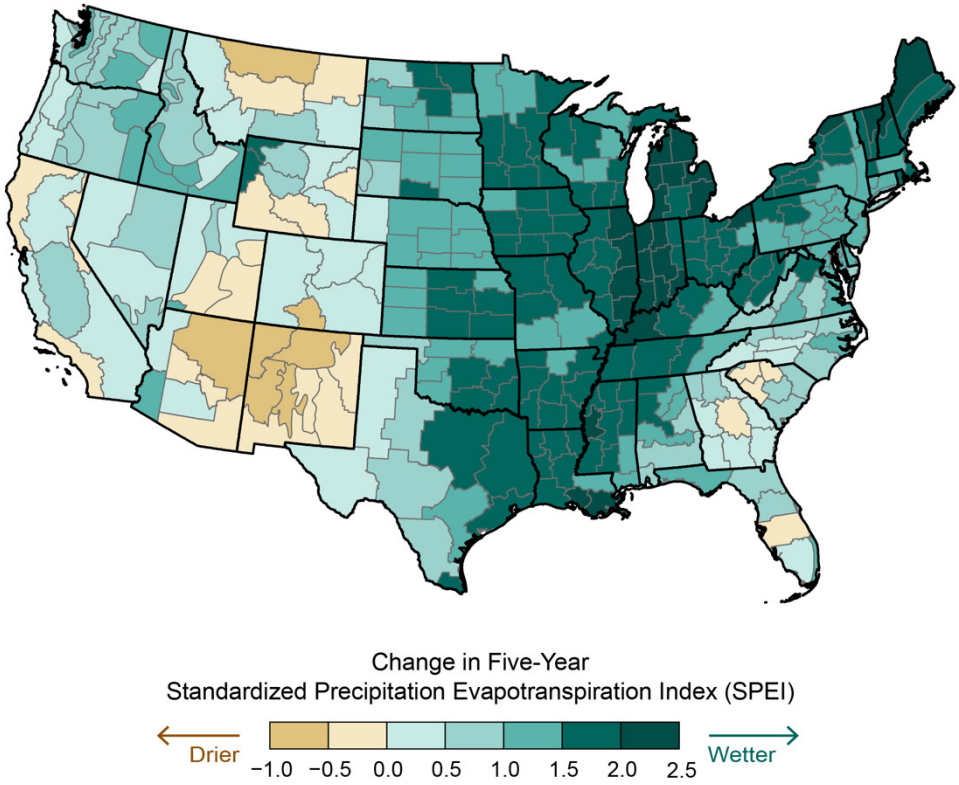
**Figure A4.8.** Flood magnitudes are increasing along the Oregon coastline, throughout large portions of the central Rockies and southern Great Plains, and in parts of the Gulf Coast, whereas flood frequencies are increasing across a large area east of the Rocky Mountain Front.[41] This indicator shows trends in (**a**) magnitude and (**b**) frequency of large floods in the western US within 117 flood potential zones. Shading in warm colors (reds) represents increasing trends, and shading in cool colors (blues) represents decreasing trends. Darker shades indicate where trends are statistically significant. (a) Percent change in annual flood magnitudes is indicated by black numbering. Trends in magnitudes vary by the available record length (most commonly from the early 1900s through 2020), while (b) trends in frequency are for 1945 to about 2020. Data are not yet available for the US Caribbean, Alaska, or Hawai'i and US-Affiliated Pacific Islands regions, as well as the contiguous US east of the Mississippi River. Additional information related to trends in large floods is provided in the Flood Potential Portal at https://floodpotential.erams.com/. Figure credit: USDA Forest Service.

## *Drought*

The effects of drought can be far-reaching and long-lasting, posing risks to people and ecosystems and often contributing to other extreme events, such as drought-induced wildfire (KM 4.2; Focus on Western Wildfires). Several hydrologic measures exist for drought, and for certain applications, climate reanalyses can also be valuable in evaluating historical trends related to climate including drought metrics (e.g., Jasinski et al. 2019[42]). Some drought indicators consider water availability, measured by variables such as precipita-

tion (Figure 4.10), streamflow, groundwater and reservoir levels, or soil moisture (Figure 28.2). Other drought indicators take into account different climatic factors, such as temperature, potential evapotranspiration, and solar radiation (Figure 3.12). For example, the Standardized Precipitation Evapotranspiration Index (SPEI; Figure A4.9) measures the combination of precipitation and evapotranspiration to determine whether a certain area is experiencing extreme drought, extreme moisture, or conditions in between.[43] SPEI is a valuable indicator when considering how droughts might affect activities that depend on a balance between water supply and demand, particularly those related to agriculture and ecosystems.[44]

### Change in Drought Conditions, 1900–2022




**Long-term records show conditions are becoming drier in many portions of the West and wetter elsewhere, particularly the East.**

**Figure A4.9.** Since the early 20th century, the eastern US has generally experienced wetter conditions, while portions of the West—especially the Southwest—have experienced drier conditions. This map shows the total change in drought conditions across the contiguous United States, based on the long-term average rate of change in the five-year Standardized Precipitation Evapotranspiration Index (SPEI) from 1900 to 2022. Data are displayed for small regions called climate divisions, as defined by NOAA.[45] Teal-shaded areas represent wetter conditions, and brown areas represent drier conditions. Data are not available for the US Caribbean, Alaska, or Hawai'i and US-Affiliated Pacific Islands regions. Adapted from EPA 2023.[44]

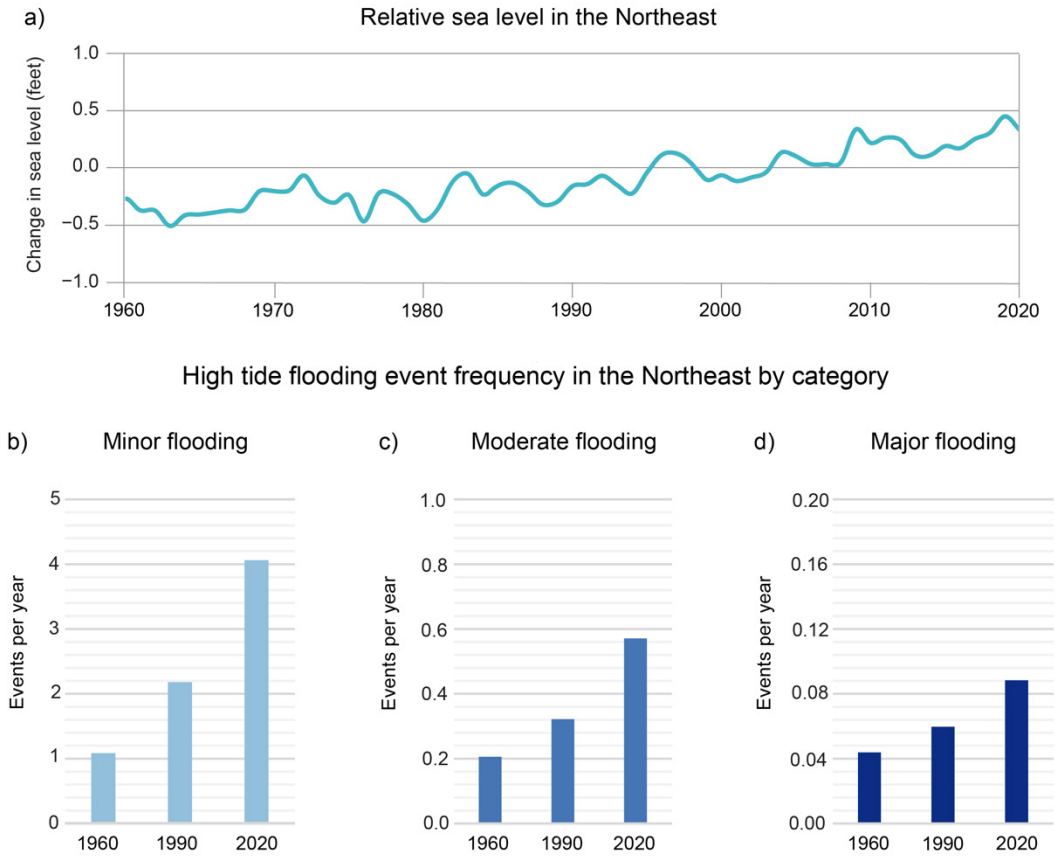
## A4.4. Ocean and Coastal Indicators

Climate-driven changes to US oceans and coasts endanger marine ecosystems and coastal communities (Figures 10.1, 21.5) and threaten infrastructure and energy production (KMs 9.2, 10.1). Indicators can be used to track physical ocean conditions (e.g., sea surface temperatures, ocean acidification), ecological impacts (e.g., marine species shifts), and coastal impacts (e.g., high tide flooding). This information is used to evaluate risk, promote resilience, and increase the value of coastal and marine resources as ocean conditions change.

## *Sea Level Rise and Coastal Flooding*

Global sea level is rising as warming ocean waters expand and glaciers and ice sheets melt. Along some US coastal areas, sea levels are rising faster than the global average, with the highest rates occurring along parts of the Atlantic coast and the Gulf of Mexico (Figures A4.10a, 2.5; KMs 21.2, 22.1, 26.1).[46] The increase in relative sea level is driving increases in physical and societal impacts such as high tide flooding (Figure A4.10b–d; KM 9.1).

### Sea Level and Coastal Flooding in the Northeast



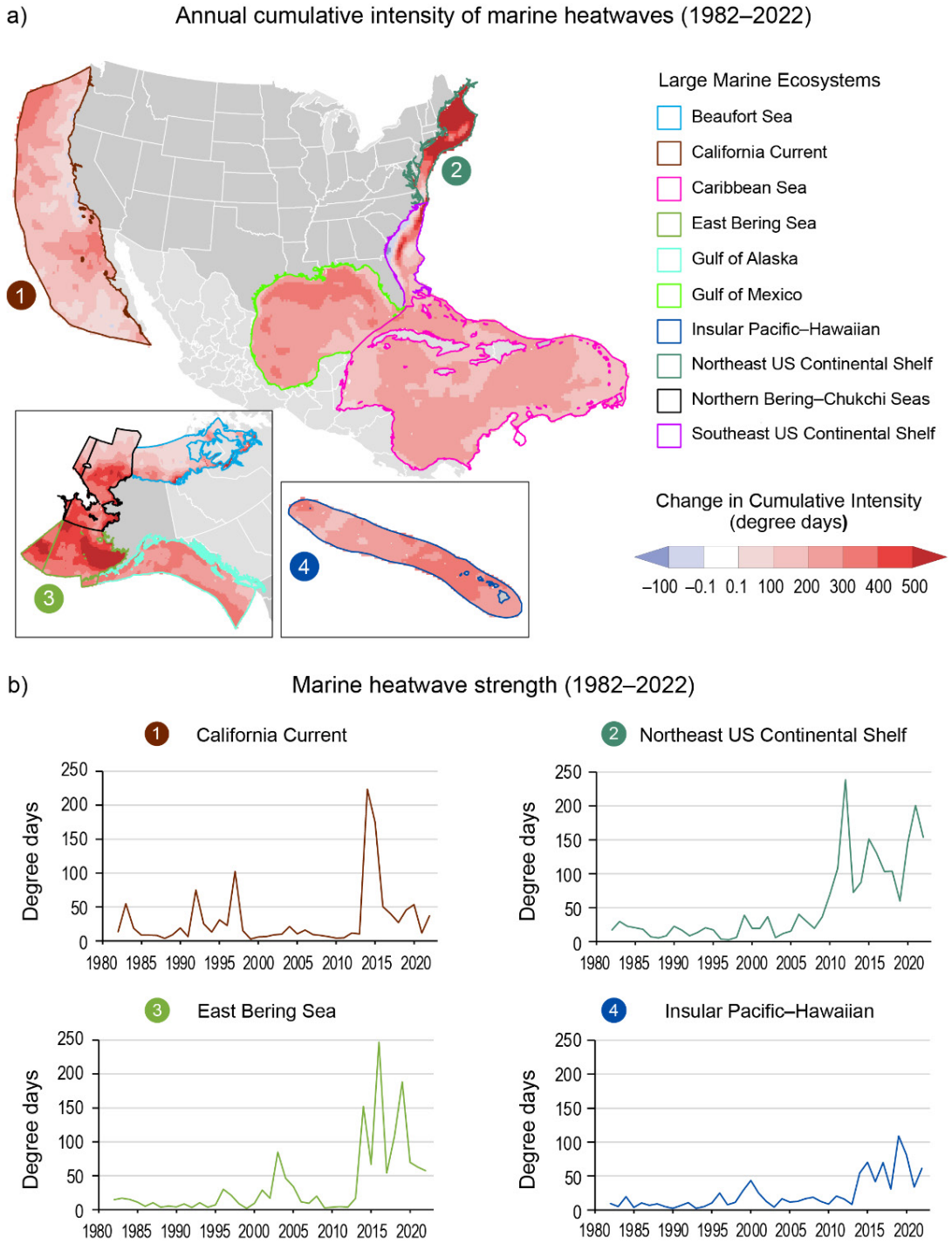

**The combination of rising sea levels and the increased frequency of coastal flooding events exacerbates risk for coastal communities.**

**Figure A4.10.** (**a**) The line chart shows the observed changes in relative sea level from 1960 to 2020 (compared to the 1991–2009 average), which is a combination of sea level changes and local uplift or subsidence of land, averaged along the Atlantic coast of the northeastern US. The bar graphs depict the frequency of (**b**) minor (disruptive), (**c**) moderate (damaging), and (**d**) major (destructive) high tide flooding events at 30-year intervals (1960, 1990, and 2020), also for the northeastern US (see Figure 9.3 for definitions of high tide flooding thresholds). The frequency of occurrence is expressed as the number of events per year, where a value of 0.1 is equivalent to a 10% annual chance of experiencing that type of flood event. See Chapter 9 for contiguous US data, including future projections. Figure credits: (a) adapted from Sweet et al. 2022;[47] (b, c, d) NOAA NCEI and NOAA.

## *Marine Heatwaves*

Sea surface temperatures in oceans surrounding the US have risen steadily over time, as they have in most of the world's oceans (Figure 2.3).[48] Rising temperatures in these areas contribute to increases in marine heatwave frequency (KMs 10.1, 21.2), intensity (Figure A4.11), size, and duration.[49] These changes have detrimental impacts on surrounding ecosystems and economies, including shifts in the distributions of marine life (Figure A4.12; KMs 8.2, 10.1).

## Marine Heatwaves



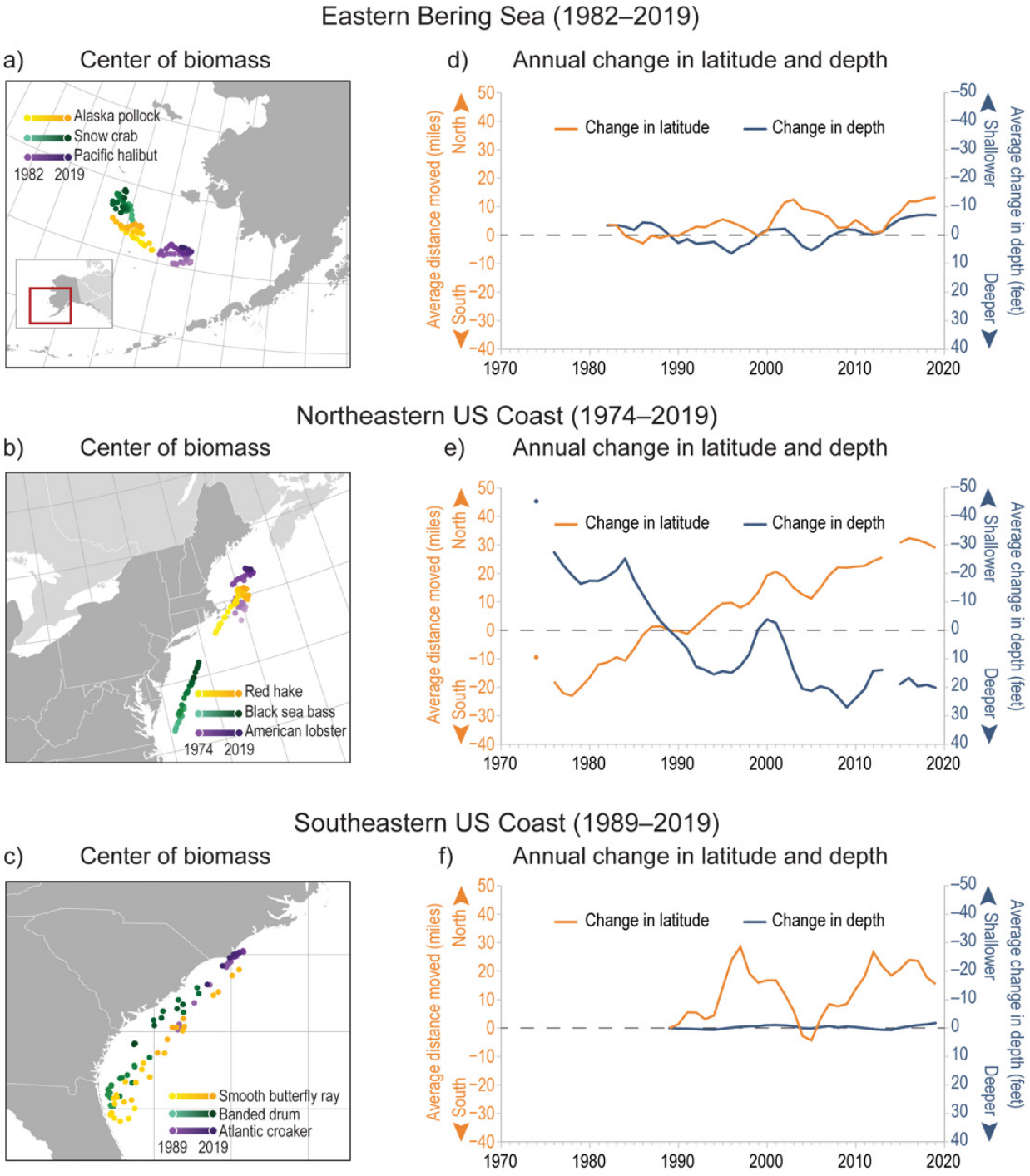

**Extreme ocean temperatures are more common as ocean temperatures rise.**

**Figure A4.11.** (**a**) The maps show the change in annual cumulative intensity of marine heatwaves (anomalously warm temperatures lasting five or more days) within large marine ecosystems surrounding the United States from 1982 to 2022. Cumulative intensity, or degree days, is determined by heatwave intensity multiplied by duration, compared to the 1982–2011 average. Areas with increases in cumulative intensity are shown in red, with darker colors indicating greater change. Areas in blue represent a decrease in cumulative intensity over time. (**b**) Charts show the heatwave strength in total degree days each year from 1982 to 2022 for select large marine ecosystems highlighted in the above maps. Figure credit: NOAA NCEI, University of Miami, DOE, and Eastern Research Group Inc.

## *Marine Species*

Warming oceans have contributed to shifts in the geographic distribution of marine species (KM 10.1), which are extensively studied and tracked using indicators.[50] It is important to track climate-driven changes in the distribution, timing, and productivity of fishery-related species that can put marine fisheries and fishing communities at risk.[51] Many marine species are sensitive to environmental cues such as temperature ranges and track well with local climate velocities (the speed and direction at which species move in order to experience similar climate conditions).[52] However, several other factors can influence the abundance and geographic distribution of species, such as large-scale fishing practices, ocean currents, changes in habitats, and species' ability to adapt. Figure A4.12 depicts how multiple species adjacent to the Alaska, northeastern US, and southeastern US coasts have been shifting northward and, in some regions deeper, to cooler waters.

## Marine Species Distribution




**Marine species along US coasts are generally shifting northward to cooler waters.**

**Figure A4.12.** (**left**) Maps show annual centers of biomass for three species in three regions: (**a**) the eastern Bering Sea (1982–2019) and the (**b**) northeastern (1974–2019) and (**c**) southeastern (1989–2019) US coasts. Species were chosen because they represent a variety of habitats and species types and are relatively abundant. Dots are shaded to show how species' locations have changed over time, with light shading representing earlier years and darker shading representing more recent years. (**right**) Charts show the annual change in latitude (orange lines; movement in miles) and depth (blue lines; change in feet) of several marine species in (**d**) the eastern Bering Sea (top; 64 species) and (**e**) the northeastern (middle; 53 species) and (**f**) southeastern (bottom; 63 species) US coasts, relative to 1989. Black dashed lines represent no overall change. Data were not available for 1975 or 2014 for the Northeast region. Adapted from EPA 2023.[50]

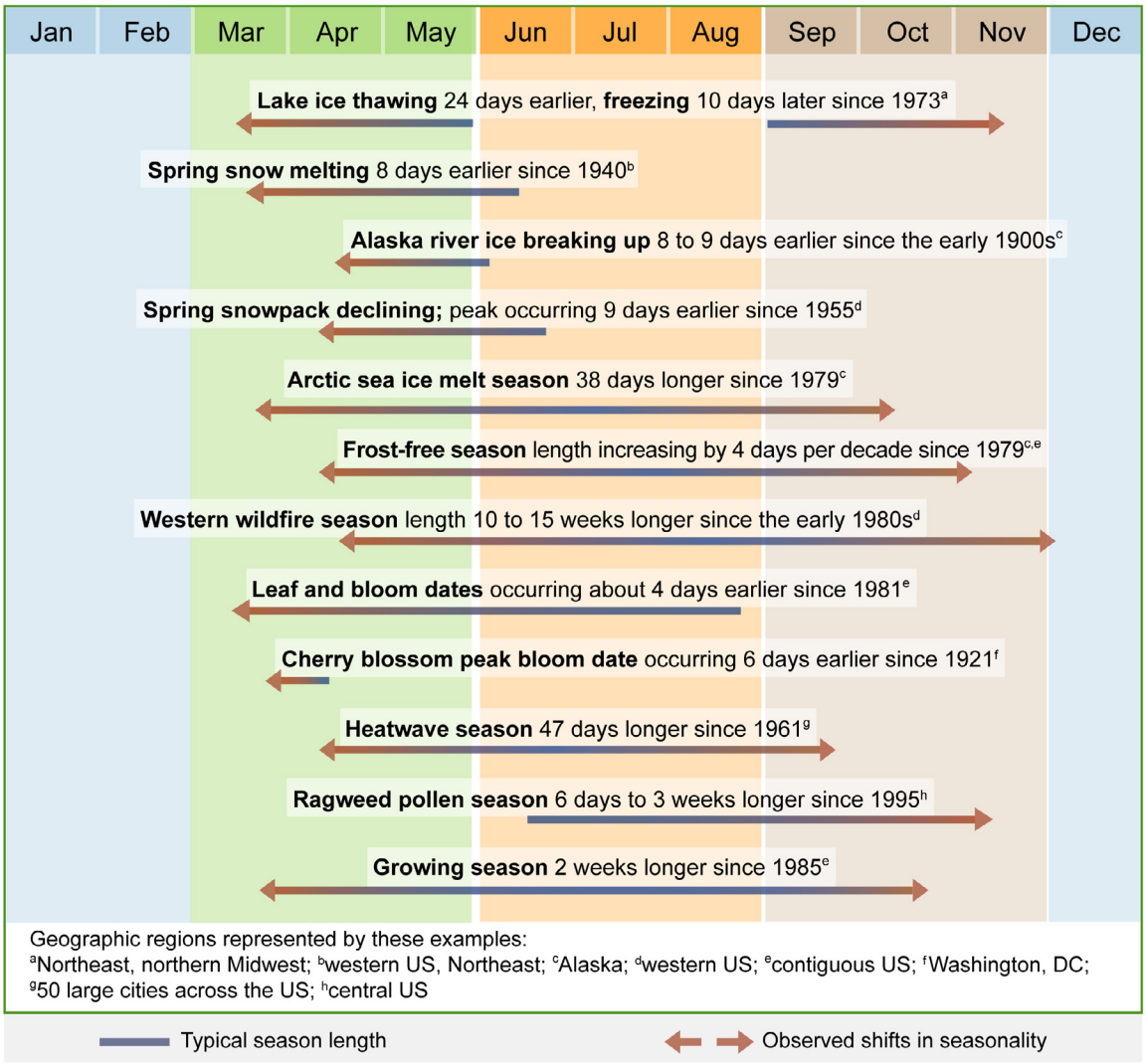
# A4.5. Land and Ecosystems Indicators

Earth's land, food, and climate systems are inextricably intertwined (Figure 11.9). Climate and weather shape demand for and distribution of food, fish, and forest products. In turn, commodity production influences the climate via greenhouse gas exchange and land conservation or degradation. These feedbacks are driving the coupled climate–land system toward a host of outcomes for people and society, some undesirable.[53] Indicators can help land managers and policymakers identify optimal planning and solutions in the context of changing conditions.

## *Seasonal Change*

Seasonality refers to recurring seasonal events or processes, such as the blooming of wildflowers in spring.[54] The timing, duration, and variability of many seasonal events are changing in response to changing temperature and moisture patterns (Chs. 2, 8; Figure 24.3). Indicators of seasonal change (Figure A4.13) are valuable for understanding relationships between climate and ecosystems and subsequent risks to environmental and social systems.[55] Knowledge of these changes is often generated by local and Indigenous populations, who have deep connections to local ecosystems because of their cultural and subsistence practices (Ch. 16).

## Changes in Seasonality



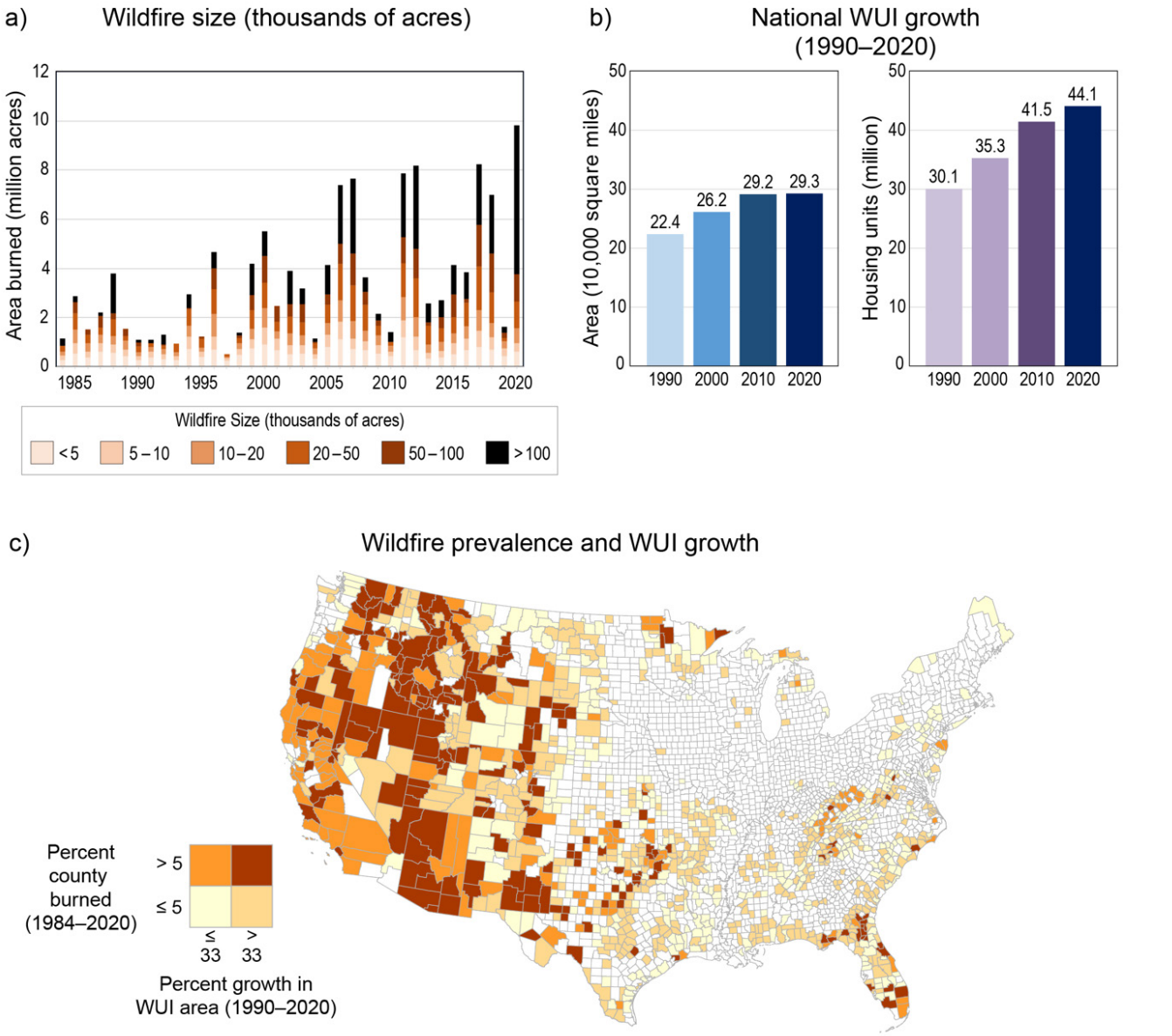

**Observed evidence of changes in seasonality reflect a warming climate.**

**Figure A4.13.** Many indicators show shifts in timing and duration of seasonal events or processes that are correlated with seasons. The length of the blue lines represents the approximate time of year when these events typically occur, and the direction of the arrows denotes earlier (←) and later (→) shifts in the season. Red line segments portray the observed change for illustrative purposes, whereas the actual observed values are provided as text above each line. Some of these indicators are limited to specific geographic regions. Adapted from EPA 2021.[54]

## *Wildland Fire and the Wildland–Urban Interface*

Wildland fires affect carbon dynamics, ecosystems, biodiversity, and human health (Ch. 7; KMs 6.1, 14.2; Figures F2.1, 28.9). The wildland–urban interface (WUI) is the area where buildings and other developments meet or mix with undeveloped natural areas, including fire-prone vegetation. Over the past several decades, the WUI has grown rapidly,[56] expanding in both total area and number of homes. In addition, the annual average acreage burned by wildfires has increased since the mid-1980s.[57] Together, these changes have increased risks of loss of life and property damage in many areas across the United States (Figure A4.14). Other important wildfire-related indicators include greenhouse gas emissions resulting from wildfires and prescribed fires (Figure 7.2) and related socioeconomic indicators such as federal spending on wildfire suppression.[58]

## Wildfires and Wildland–Urban Interface (WUI) Growth



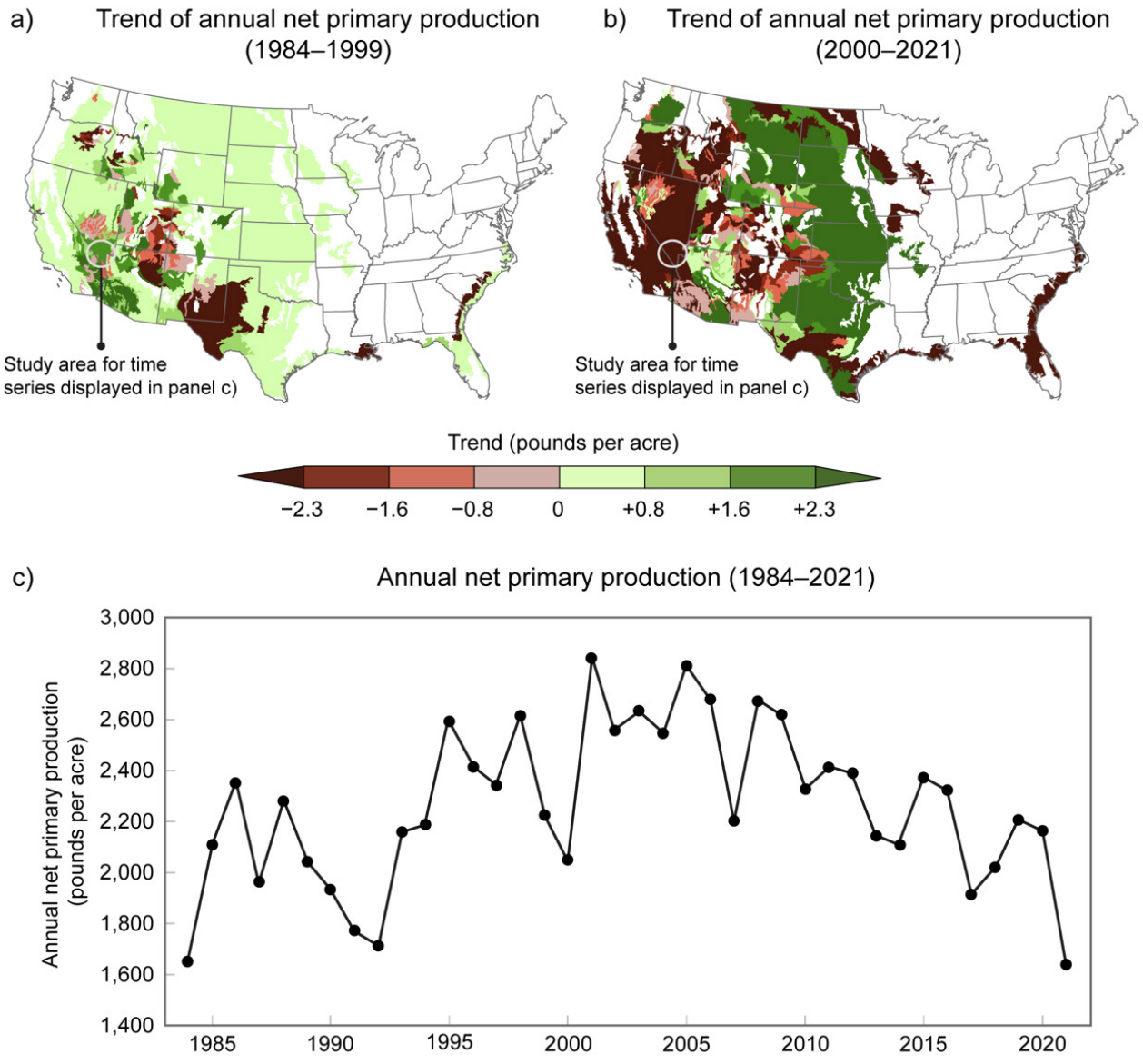

**Area burned by wildfires is increasing and the wildland–urban interface is expanding in the contiguous US.**

**Figure A4.14.** (**a**) The chart shows the number of acres burned between 1984 and 2020 for the contiguous US. The different shades within each bar indicate the proportional contribution of different fire size classes to the total for that year. (**b**) The two charts depict wildland–urban interface (WUI) growth in terms of area and number of housing units from 1990 to 2020 for the contiguous US. (**c**) The map portrays US counties where WUI growth and wildfires are most prevalent. Counties are categorized by their level of WUI growth between 1990 and 2020 and area burned between 1984 and 2020. Counties are not categorized where wildfires do not meet the minimum size requirements for Monitoring Trends in Burn Severity (MTBS) mapping[57] or where percent growth in WUI area is less than zero. WUI data are not available for the US Caribbean, Alaska, or Hawai'i and US-Affiliated Pacific Islands regions. In Alaska, wildfires burned over 34 million acres between 1984 and 2020; during this period, eight of the nine wildfire seasons when more than one million acres burned have occurred since 2000. Twenty-one wildfires in Hawai'i (more than 103,000 total acres) and four wildfires in Puerto Rico (about 6,300 total acres) were mapped between 1984 and 2020. MTBS wildfire data are not available for other parts of the US Caribbean and US-Affiliated Pacific Islands regions (wildfire data from another source for the US-Affiliated Pacific Islands region is presented in Figure 30.13). Figure credits: (a, c) USDA Forest Service; (b) adapted from Radeloff et al. 2018.[56]

## *Agriculture and Food Systems*

The climate–agriculture–food system is complex (Figure 11.9). Agricultural production and natural resources face challenges from increasing climate variability and change. Optimized management and policy decisions require an integrated indicator system that communicates climate-driven production impacts; trends in the social-ecological systems underpinning agriculture (e.g., heat-related mortality of workers; Figure 11.1); crop insurance payments (KM 11.2);[5] how management performs in relation to desired social-ecological conditions;[59] degree of adaptation (KM 11.1); and the relationships among climate change, consumption, and production.[60] Currently, the most developed agriculture-related indicators are production-oriented (Ch. 11), such as range or crop yield, crop pathogens, animal heat stress, migration of plant hardiness zones (Figure 11.3), timing of budbreak in fruit trees, and ratios of outputs to inputs (total factor productivity).[5] The productivity of rangeland vegetation provides many valued ecosystem services,[61] but it has severely declined in some areas of the US in recent decades (Figure A4.15),[62] with a strong correlation to regional-scale climate change exposure.[63]

## Rangeland Production




**Rangeland vegetation production has severely declined in some areas and increased in others.**

**Figure A4.15.** Rangeland annual net primary production (ANPP) measures the annual production of rangeland vegetation, which provides key ecosystem services supporting soil, air, and water quality and billions of dollars in commerce. This figure illustrates ANPP in pounds per acre on rangelands by ecological subsection (see Cleland et al. 2007[64]) during the periods (**a**) 1984–1999 and (**b**) 2000–2021. Positive values indicate areas where ANPP has increased over time, and negative values show where it has decreased. Areas in white are not classified as rangeland ecosystems. (**c**) The time series shows annual values of ANPP from 1984 to 2021 for a select location in the Mojave Desert (indicated by the circle on the maps). ANPP increased in this area over the first half of the time period but has since seen a steady decline. Data are not available for the US Caribbean, Alaska, or Hawai'i and US-Affiliated Pacific Islands regions. Adapted with permission from Reeves et al. 2021[62] [CC BY-NC-ND 4.0].

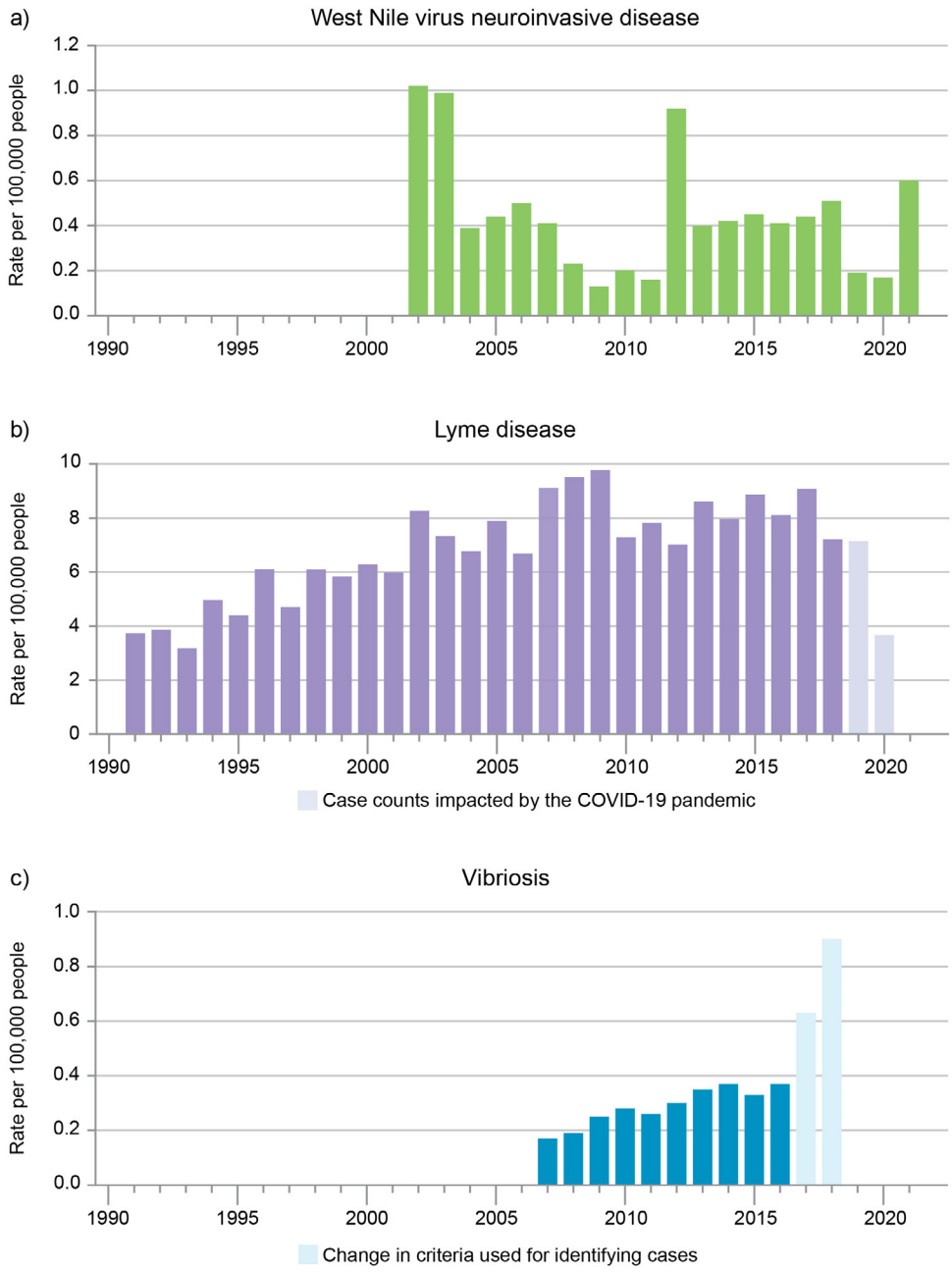
# A4.6. Health Indicators

Climate change increases risks and impacts to human health and well-being by exacerbating existing health threats and creating new challenges based on multiple factors and pathways. A variety of health outcomes are affected by climate change, including mental health challenges as well as physical health issues such as cardiorespiratory conditions from poor air quality, injuries and mortality from extreme weather events, and malnutrition from changing climate and environmental factors.[15]

It is important that health indicators include more than just measures of health outcomes to understand how climate impacts and exposures influence health burdens. A broader approach is helpful because of the complex, often indirect relationships among climate drivers, environmental and social factors, and health outcomes, and because of challenges with collecting and reporting health data including lag times in availability. Some widely utilized health indicators include heat-related illnesses and deaths,[21,22,65] described in part in NCA4, which also details the impacts of a changing climate on vector-, water-, and foodborne diseases but without quantitative context.[66] To build upon this body of knowledge and to highlight robust examples of infectious disease metrics with 1) strong science supporting the linkages among climate, environment, and human risk factors; 2) national coverage; and 3) ample temporal extent, this appendix presents indicators for three nationally notifiable infectious diseases routinely reported to the CDC (Figure A4.16).

Changes in temperature, precipitation patterns, and extreme events can alter the seasonality, distribution, and prevalence of vector-, water-, and foodborne diseases (KM 15.1).[7] West Nile virus (WNV) neuroinvasive disease and Lyme disease are impacted by climate change through complex shifts in land use, vector ecology, and human behavior (Chs. 8, 15). Vibriosis, linked to warming marine and coastal waters, is an illness contracted through exposure to *Vibrio* bacterial species from contaminated seafood or from open skin wounds exposed to contaminated water.[7]

## Infectious Diseases Impacted by Climate Change



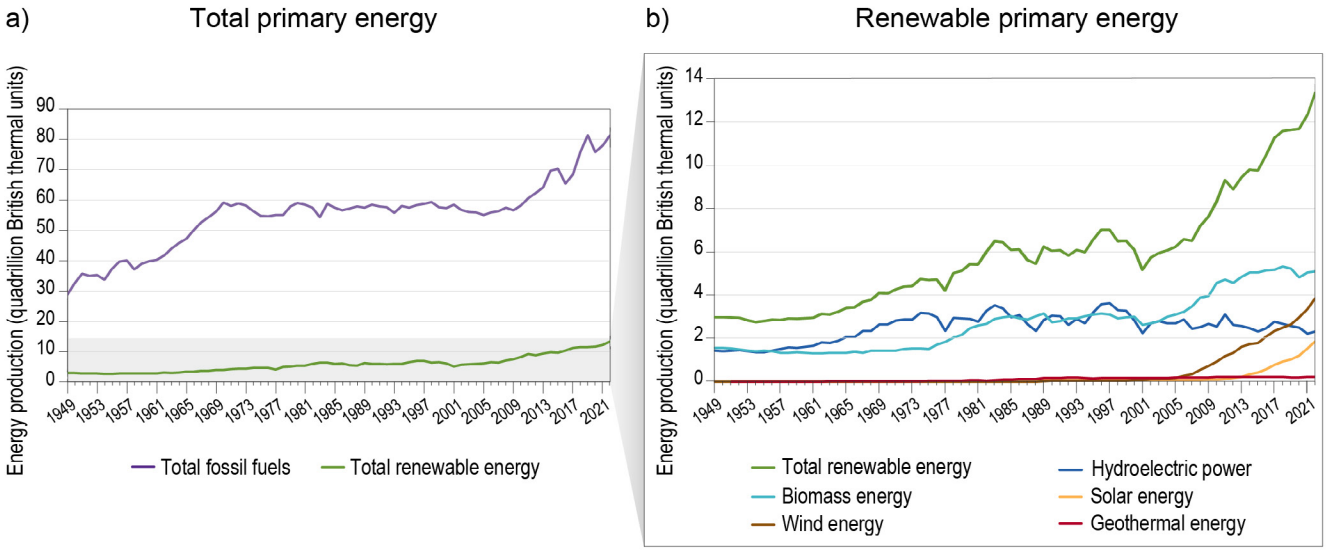

**Climate, environmental, and social factors influence infectious disease rates.**

**Figure A4.16.** Indicators of diseases widely recognized as being affected by climate change can provide a general gauge of the disease burden and help guide resources and public health actions. Incidence rates of (**a**) West Nile virus (WNV) neuroinvasive disease, (**b**) Lyme disease, and (**c**) vibriosis are presented for the years 2002–2021, 1991–2020, and 2007–2018, respectively. For WNV neuroinvasive disease, the pattern of incidence rates is variable, ranging from 1 per 100,000 people in 2002, when it became a nationally notifiable condition, to 0.6 per 100,000 people in 2021. Lyme disease incidence rates have trended upward from 4 cases per 100,000 people in 1991 to 7 cases per 100,000 in 2018. Similarly, trends in vibriosis have risen since 2007. Confirmed and probable cases are collected by state and local health departments and reported to the National Notifiable Diseases Surveillance System or the COVIS (Cholera and Other *Vibrio* Illness Surveillance) system. Annual counts and rates for each state are compiled by the CDC. Surveillance data for Lyme disease in 2019 and 2020 were markedly affected by the COVID-19 pandemic (light purple bars). Case definitions are occasionally revised, but because the vibriosis case definition changed significantly in 2017, trends before (dark blue bars) and after (light blue bars) are not comparable. (a) Adapted from EPA 2023;[67] (b) adapted from EPA 2023;[68] (c) adapted from Sheahan et al. 2022.[69]

# A4.7. Adaptation and Mitigation Indicators

Adaptation to promote climate resilience of populations, ecosystems, and infrastructure as well as mitigation to reduce emissions are critical, particularly for protecting human well-being and the environment (Chs. 31, 32). Indicators of adaptation and mitigation are important tools that help track and assess progress[70,71,72], as well as evaluate adaptation decisions and improve resilience (KM 31.5). This can be done, for example, by aggregating the number of documented adaptation activities by state over a certain time period (Figures 1.3, 31.1, 32.20). Although valuable for decision-making and evaluating effectiveness, indicators of resilience, adaptation responses, and adaptive capacity remain relatively limited.[72,73,74] Figure A4.17 is an example of a mitigation indicator showing how US energy production from renewables has increased in recent years (KM 32.1; Figures 26.6, 32.3).

## Energy Production by Source




**US energy production from renewables is increasing.**

**Figure A4.17.** The figure shows annual time series of US energy production for (**a**) total primary energy (which includes both fossil fuels and renewable energy) and (**b**) categories of renewable energy (biomass, wind, hydroelectric, solar, and geothermal) for 1949–2022. US energy production from renewable sources (dark green line) has increased since the 1960s, reaching a record high in 2022, primarily due to increases in wind (brown line) and biomass (light blue line) energy. Energy production from fossil fuels (purple line) also increased during this same time period, although with increased use of cleaner fossil fuels (KM 5.3). Adapted from EIA 2023.[75]

Climate change disproportionately impacts certain communities and populations (Ch. 20). Social, environmental, and economic factors[76,77,78] contribute to disparities experienced by groups at greater risk of climate change stressors (KM 15.2). Indices that combine multiple variables have been developed to capture complex issues affecting communities that are overburdened (e.g., Figures 15.5, 22.12). Furthermore, indicators that couple human and social dimensions with climate data (e.g., Figures 11.13, 12.6, 22.18) are necessary to better assess who is at highest risk from impacts and to prioritize and evaluate response decisions.

# A4.8. Knowledge Gaps and New Approaches

It is vital to recognize data specific to Indigenous communities to adequately address the disproportionate impacts of climate change (Ch. 16).[79] Indicators drawing from Indigenous Knowledge (KM 16.3)[80] and focusing on the concept of cultural keystone indicator species[81] may better represent the perspectives of Indigenous Peoples affected by climate change than the indicators featured in this appendix.

Indicators are used to evaluate community response and preparedness,[82] as well as the capacity for socio-ecological systems to build resilience.[83] However, it is difficult to incorporate consistent indicators of resilience and adaptation (e.g., Brooks 2014;[84] Keenan and Maxwell 2021[85]). Distilling best practices at the community scale remains a challenge.[86] The emerging understanding of compound events and their impacts (Ch. 18) will likely inform new indicator development. Confidence in attributing outcomes to climate change varies among physical climate indicators, especially for societal and ecosystem indicators (e.g., IPCC 2022[15]).

Data sharing and transparency standards arising from the Information Quality Act (IQA; App. 2), are well established for geophysical information and are reliably compiled in several recurring volumes,[2,9,87] whereas biological and health information is typically built on local and less-federated data. For health, limitations in sharing data, due to privacy concerns or cost, hinder the creation of nationally consistent indicators.[8] Advances in applying IQA standards to nonphysical data will increase the availability and credibility of this information.

Newer observing systems and sensors and community-led ("citizen") science bring additional data options. In recent years, broader public participation in data collection and curation has played an increasingly important role in contributing to existing or potential indicators. Such efforts include improvements in documenting physical climate variables at finer scales,[88] capturing the impacts on or responses of ecosystems, and recording climate-related influences on human health.[89]

While indicators provide valuable information on past changes, it is important that they be well positioned to provide information on how these changes may continue in the future, to assist with planning, adaptation, and strategic policy decisions. For example, national surveillance systems, such as the National Notifiable Diseases Surveillance System,[90] could integrate indicators into existing data collection and analysis processes to advance interpretation of observed data, trends, and impacts. New indicators that track how compound events are changing over time would potentially help communities become more climate resilient (see Focus on Compound Events).

Looking ahead, indicator systems that reflect the coupled nature of climate systems and management systems will be needed for optimal planning and policymaking. This will require integration across disciplines, stakeholder groups, government agencies, and nations.[91]

# References


1. Jay, A., D.R. Reidmiller, C.W. Avery, D. Barrie, B.J. DeAngelo, A. Dave, M. Dzaugis, M. Kolian, K.L.M. Lewis, K. Reeves, and D. Winner, 2018: Ch. 1. Overview. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 33–71. https://doi.org/10.7930/nca4.2018.ch1

2. EPA, 2023: Climate Change Indicators in the United States. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators

3. Di Napoli, C., A. McGushin, M. Romanello, S. Ayeb-Karlsson, W. Cai, J. Chambers, S. Dasgupta, L.E. Escobar, I. Kelman, T. Kjellstrom, D. Kniveton, Y. Liu, Z. Liu, R. Lowe, J. Martinez-Urtaza, C. McMichael, M. Moradi-Lakeh, K.A. Murray, M. Rabbaniha, J.C. Semenza, L. Shi, M. Tabatabaei, J.A. Trinanes, B.N. Vu, C. Brimicombe, and E.J. Robinson, 2022: Tracking the impacts of climate change on human health via indicators: Lessons from the Lancet Countdown. *BMC Public Health*, **22** (1), 663. https://doi.org/10.1186/s12889-022-13055-6

4. Kenney, M.A., A.C. Janetos, and M.D. Gerst, 2020: A framework for national climate indicators. *Climatic Change*, **163** (4), 1705–1718. https://doi.org/10.1007/s10584-018-2307-y

5. Walsh, M.K., P. Backlund, L. Buja, A. DeGaetano, R. Melnick, L. Prokopy, E. Takle, D. Todey, and L. Ziska, 2020: Climate Indicators for Agriculture. USDA Technical Bulletin 1953. U.S. Department of Agriculture, Washington, DC, 70 pp. https://doi.org/10.25675/10217/210930

6. Romanello, M., C. Di Napoli, P. Drummond, C. Green, H. Kennard, P. Lampard, D. Scamman, N. Arnell, S. Ayeb-Karlsson, L.B. Ford, K. Belesova, K. Bowen, W. Cai, M. Callaghan, D. Campbell-Lendrum, J. Chambers, K.R. van Daalen, C. Dalin, N. Dasandi, S. Dasgupta, M. Davies, P. Dominguez-Salas, R. Dubrow, K.L. Ebi, M. Eckelman, P. Ekins, L.E. Escobar, L. Georgeson, H. Graham, S.H. Gunther, I. Hamilton, Y. Hang, R. Hänninen, S. Hartinger, K. He, J.J. Hess, S.-C. Hsu, S. Jankin, L. Jamart, O. Jay, I. Kelman, G. Kiesewetter, P. Kinney, T. Kjellstrom, D. Kniveton, J.K.W. Lee, B. Lemke, Y. Liu, Z. Liu, M. Lott, M.L. Batista, R. Lowe, F. MacGuire, M.O. Sewe, J. Martinez-Urtaza, M. Maslin, L. McAllister, A. McGushin, C. McMichael, Z. Mi, J. Milner, K. Minor, J.C. Minx, N. Mohajeri, M. Moradi-Lakeh, K. Morrissey, S. Munzert, K.A. Murray, T. Neville, M. Nilsson, N. Obradovich, M.B. O'Hare, T. Oreszczyn, M. Otto, F. Owfi, O. Pearman, M. Rabbaniha, E.J.Z. Robinson, J. Rocklöv, R.N. Salas, J.C. Semenza, J.D. Sherman, L. Shi, J. Shumake-Guillemot, G. Silbert, M. Sofiev, M. Springmann, J. Stowell, M. Tabatabaei, J. Taylor, J. Triñanes, F. Wagner, P. Wilkinson, M. Winning, M. Yglesias-González, S. Zhang, P. Gong, H. Montgomery, and A. Costello, 2022: The 2022 report of the *Lancet* Countdown on health and climate change: Health at the mercy of fossil fuels. *The Lancet*, **400** (10363), 1619–1654. https://doi.org/10.1016/s0140-6736(22)01540-9

7. USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp. https://doi.org/10.7930/j0r49nqx

8. Liu, A.Y., J.M. Trtanj, E.K. Lipp, and J.M. Balbus, 2021: Toward an integrated system of climate change and human health indicators: A conceptual framework. *Climatic Change*, **166** (3), 49. https://doi.org/10.1007/s10584-021-03125-w

9. USGCRP, 2023: USGCRP Indicators Platform. U.S. Global Change Research Program, accessed October 3, 2023. https://www.globalchange.gov/indicators/

10. CDC, 2020: National Environmental Public Health Tracking: Climate Change. Centers for Disease Control and Prevention, accessed April 5, 2023. https://www.cdc.gov/nceh/tracking/topics/climatechange.htm

11. EPA, n.d.: EPA Climate Indicator Map Viewer. U.S. Environmental Protection Agency, accessed May 20, 2023. https://experience.arcgis.com/experience/bdd9567a847a4b52abd20253539143df

12. NASA, 2023: Global Climate Change—Vital Signs of the Planet: Understanding Our Planet to Benefit Humankind. National Aeronautics and Space Administration. https://climate.nasa.gov/

13. NOAA, 2023: National Marine Ecosystem Status: Assessing Our Marine and Great Lakes Ecosystems. National Oceanic and Atmospheric Administration, accessed May 5, 2023. https://ecowatch.noaa.gov/

14. Kunkel, K.E., R. Frankson, J. Runkle, S.M. Champion, L.E. Stevens, D.R. Easterling, B.C. Stewart, A. McCarrick, and C.R. Lemery, 2022: State Climate Summaries for the United States 2022. NOAA Technical Report NESDIS 150. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. https://statesummaries.ncics.org/

15. IPCC, 2022: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844

16. UN Environment Programme, n.d.: About Montreal Protocol. United Nations Environment Programme. https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol

17. USGCRP, 2023: USGCRP Indicators Platform: Annual Greenhouse Gas Index. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/annual-greenhouse-gas-index

18. EPA, 2023: Climate Change Indicators: Seasonal Temperature. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-seasonal-temperature

19. Raymond, C., T. Matthews, R.M. Horton, E.M. Fischer, S. Fueglistaler, C. Ivanovich, L. Suarez-Gutierrez, and Y. Zhang, 2021: On the controlling factors for globally extreme humid heat. *Geophysical Research Letters*, **48** (23), e2021GL096082. https://doi.org/10.1029/2021gl096082

20. Rogers, C.D.W., M. Ting, C. Li, K. Kornhuber, E.D. Coffel, R.M. Horton, C. Raymond, and D. Singh, 2021: Recent increases in exposure to extreme humid-heat events disproportionately affect populated regions. *Geophysical Research Letters*, **48** (19), e2021GL094183. https://doi.org/10.1029/2021gl094183

21. EPA, 2023: Climate Change Indicators: Heat Related Illneses. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/heat-related-illnesses

22. EPA, 2023: Climate Change Indicators: Heat Related Deaths. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-heat-related-deaths

23. USGCRP, 2023: USGCRP Indicators Platform: Heat Waves. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/heat-waves

24. Xian, G., H. Shi, Q. Zhou, R. Auch, K. Gallo, Z. Wu, and M. Kolian, 2022: Monitoring and characterizing multi-decadal variations of urban thermal condition using time-series thermal remote sensing and dynamic land cover data. *Remote Sensing of Environment*, **269**, 112803. https://doi.org/10.1016/j.rse.2021.112803

25. Kunkel, K.E., T.R. Karl, M.F. Squires, X. Yin, S.T. Stegall, and D.R. Easterling, 2020: Precipitation extremes: Trends and relationships with average precipitation and precipitable water in the contiguous United States. *Journal of Applied Meteorology and Climatology*, **59** (1), 125–142. https://doi.org/10.1175/jamc-d-19-0185.1

26. EPA, 2023: Climate Change Indicators: Heavy Precipitation. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-heavy-precipitation

27. USGCRP, 2023: USGCRP Indicators Platform: Atlantic Tropical Cyclone Days. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/atlantic-tropical-cyclone-days

28. Smith, A.B., 2022: 2021 U.S. Billion-Dollar Weather and Climate Disasters in Historical Context. National Oceanic and Atmospheric Administration, National Centers for Environmental Information. https://www.climate.gov/news-features/blogs/beyond-data/2021-us-billion-dollar-weather-and-climate-disasters-historical

29. NCEI, 2023: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

30. USGCRP, 2023: USGCRP Indicators Platform: Billion Dollar Disasters. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/billion-dollar-disasters

31. Peters-Lidard, C.D., K.C. Rose, J.E. Kiang, M.L. Strobel, M.L. Anderson, A.R. Byrd, M.J. Kolian, L.D. Brekke, and D.S. Arndt, 2021: Indicators of climate change impacts on the water cycle and water management. *Climatic Change*, **165** (1-2), 36. https://doi.org/10.1007/s10584-021-03057-5

32. Stevens, L.E., T.K. Maycock, and B.C. Stewart, 2021: Climate change in the human environment: Indicators and impacts from the Fourth National Climate Assessment. *Journal of the Air & Waste Management Association*, **71** (10), 1210–1233. https://doi.org/10.1080/10962247.2021.1942321

33. EPA, 2023: Climate Change Indicators: Arctic Sea Ice. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-arctic-sea-ice

34. NOAA, 2023: Arctic Report Card. National Oceanic and Atmospheric Administration, accessed May 5, 2023. https://www.arctic.noaa.gov/report-card

35. USGCRP, 2023: USGCRP Indicators Platform: Arctic Sea Ice Extent. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/arctic-sea-ice-extent

36. CRS, 2023: Changes in the Arctic: Background and Issues for Congress. CRS Report R41153. Congressional Research Service. https://crsreports.congress.gov/product/pdf/r/r41153

37. NSIDC, 2023: Sea Ice Index Daily and Monthly Image Viewer. University of Colorado Boulder, National Snow and Ice Data Center, Boulder, CO, accessed March 6, 2023. https://nsidc.org/data/seaice_index/data-and-image-archive

38. EPA, 2023: Climate Change Indicators: Snowpack. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-snowpack

39. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. https://doi.org/10.1038/s41558-022-01290-z

40. EPA, 2023: Climate Change Indicators: River Flooding. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding

41. USFS, 2022: National Stream and Aquatic Ecology Center: Flood Potential. U.S. Department of Agriculture, Forest Service, accessed March 31, 2022. https://www.fs.usda.gov/biology/nsaec/projects-floodpotential.html

42. Jasinski, M.F., J.S. Borak, S.V. Kumar, D.M. Mocko, C.D. Peters-Lidard, M. Rodell, H. Rui, H.K. Beaudoing, B.E. Vollmer, K.R. Arsenault, B. Li, J.D. Bolten, and N. Tangdamrongsub, 2019: NCA-LDAs: Overview and analysis of hydrologic trends for the National Climate Assessment. *Journal of Hydrometeorology*, **20** (8), 1595–1617. https://doi.org/10.1175/jhm-d-17-0234.1

43. Vicente-Serrano, S.M., S. Beguería, and J.I. López-Moreno, 2010: A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration Index. *Journal of Climate*, **23** (7), 1696–1718. https://doi.org/10.1175/2009jcli2909.1

44. EPA, 2023: Climate Change Indicators: Drought. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-drought

45. NCEI, n.d.: CONUS Climate Divisions. National Oceanic and Atmospheric Administration, National Centers for Environmental Information, accessed August 16, 2023. https://www.ncei.noaa.gov/access/monitoring/reference-maps/conus-climate-divisions

46. NOAA, 2023: Tides & Currents: Relative Sea Level Trends. National Oceanic and Atmospheric Administration, accessed May 5, 2023. https://tidesandcurrents.noaa.gov/sltrends/

47. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

48. NOAA, 2023: National Marine Ecosystems Status: Sea Surface Temperature. National Oceanic and Atmospheric Administration, accessed May 5, 2023. https://ecowatch.noaa.gov/thematic/sea-surface-temperature

49. Oliver, E.C.J., M.G. Donat, M.T. Burrows, P.J. Moore, D.A. Smale, L.V. Alexander, J.A. Benthuysen, M. Feng, A. Sen Gupta, A.J. Hobday, N.J. Holbrook, S.E. Perkins-Kirkpatrick, H.A. Scannell, S.C. Straub, and T. Wernberg, 2018: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, **9** (1), 1324. https://doi.org/10.1038/s41467-018-03732-9

50. EPA, 2023: Climate Change Indicators: Marine Species Distribution. U.S. Environmental Protection Agency, accessed March 3, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-marine-species-distribution

51. USGCRP, 2023: USGCRP Indicators Platform: Marine Species Distribution. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/marine-species-distribution

52. Pinsky, M.L., B. Worm, M.J. Fogarty, J.L. Sarmiento, and S.A. Levin, 2013: Marine taxa track local climate velocities. *Science*, **341** (6151), 1239–1242. https://doi.org/10.1126/science.1239352

53. Wieland, A., 2021: Dancing the supply chain: Toward transformative supply chain management. *Journal of Supply Chain Management*, **57** (1), 58–73. https://doi.org/10.1111/jscm.12248

54. EPA, 2021: Seasonality and Climate Change: A Review of Observed Evidence in the United States. EPA 430-R-21-002. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2021-12/30339_epa_report_climate_change_and_seasonality_v12_release_508.pdf

55. Weltzin, J.F., J.L. Betancourt, B.I. Cook, T.M. Crimmins, C.A.F. Enquist, M.D. Gerst, J.E. Gross, G.M. Henebry, R.A. Hufft, M.A. Kenney, J.S. Kimball, B.C. Reed, and S.W. Running, 2020: Seasonality of biological and physical systems as indicators of climatic variation and change. *Climatic Change*, **163** (4), 1755–1771. https://doi.org/10.1007/s10584-020-02894-0

56. Radeloff, V.C., D.P. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar-Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, and S.I. Stewart, 2018: Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (13), 3314–3319. https://doi.org/10.1073/pnas.1718850115

57. Monitoring Trends in Burn Severity, 2022: MTBS Data Access: Fire Level Geospatial Data. U.S. Department of Agriculture, Forest Service, and U.S. Geological Survey, accessed March 31, 2022. http://mtbs.gov/direct-download

58. CBO, 2022: Wildfires. Congressional Budget Office. https://www.cbo.gov/publication/58212

59. Ahlering, M.A., C. Kazanski, P.E. Lendrum, P. Borrelli, W. Burnidge, L. Clark, C. Ellis, K. Gadzia, J. Gelbard, S. Gennet, J. Goodwin, J.E. Herrick, E. Kachergis, C. Knapp, N. Labbe, K. Maczko, E. Porzig, D. Rizzo, S. Spiegal, and C. Wilson, 2021: A synthesis of ranch-level sustainability indicators for land managers and to communicate across the US beef supply chain. *Rangeland Ecology & Management*, **79**, 217–230. https://doi.org/10.1016/j.rama.2021.08.011

60. van Selm, B., A. Frehner, I.J.M. de Boer, O. van Hal, R. Hijbeek, M.K. van Ittersum, E.F. Talsma, J.P. Lesschen, C.M.J. Hendriks, M. Herrero, and H.H.E. van Zanten, 2022: Circularity in animal production requires a change in the EAT-Lancet diet in Europe. *Nature Food*, **3** (1), 66–73. https://doi.org/10.1038/s43016-021-00425-3

61. Havstad, K.M., D.P.C. Peters, R. Skaggs, J. Brown, B. Bestelmeyer, E. Fredrickson, J. Herrick, and J. Wright, 2007: Ecological services to and from rangelands of the United States. *Ecological Economics*, **64** (2), 261–268. https://doi.org/10.1016/j.ecolecon.2007.08.005

62. Reeves, M.C., B.B. Hanberry, H. Wilmer, N.E. Kaplan, and W.K. Lauenroth, 2021: An assessment of production trends on the Great Plains from 1984 to 2017. *Rangeland Ecology and Management*, **78**, 165–179. https://doi.org/10.1016/j.rama.2020.01.011

63. Briske, D.D., L.A. Joyce, H.W. Polley, J.R. Brown, K. Wolter, J.A. Morgan, B.A. McCarl, and D.W. Bailey, 2015: Climate-change adaptation on rangelands: Linking regional exposure with diverse adaptive capacity. *Frontiers in Ecology and the Environment*, **13** (5), 249–256. https://doi.org/10.1890/140266

64. Cleland, D.T., J.A. Freeouf, J.E. Keys, G.J. Nowacki, C.A. Carpenter, and W.H. McNab, 2007: Ecological Subregions: Sections and Subsections for the Conterminous United States. Gen. Tech. Report WO-76D. Department of Agriculture, Forest Service, Washington, DC. https://doi.org/10.2737/wo-gtr-76d

65. CDC, 2023: Heat & Health Tracker. Centers for Disease Control and Prevention, accessed April 5, 2023. https://ephtracking.cdc.gov/Applications/heatTracker/

66. Ebi, K.L., J.M. Balbus, G. Luber, A. Bole, A. Crimmins, G. Glass, S. Saha, M.M. Shimamoto, J. Trtanj, and J.L. White-Newsome, 2018: Ch. 14. Human health. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 539–571. https://doi.org/10.7930/nca4.2018.ch14

67. EPA, 2023: Climate Change Indicators: West Nile Virus. U.S. Environmental Protection Agency, accessed March 3, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-west-nile-virus

68. EPA, 2023: Climate Change Indicators: Lyme Disease. U.S. Environmental Protection Agency, accessed March 3, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-lyme-disease

69. Sheahan, M., C.A. Gould, J.E. Neumann, P.L. Kinney, S. Hoffmann, C. Fant, X. Wang, and M. Kolian, 2022: Examining the relationship between climate change and vibriosis in the United States: Projected health and economic impacts for the 21st century. *Environmental Health Perspectives*, **130** (8), 087007. https://doi.org/10.1289/ehp9999a

70. Cutter, S.L., B.J. Boruff, and W.L. Shirley, 2003: Social vulnerability to environmental hazards. *Social Science Quarterly*, **84** (2), 242–261. https://doi.org/10.1111/1540-6237.8402002

71. Hicke, J.A., S. Lucatello, L.D. Mortsch, J. Dawson, M.D. Aguilar, C.A.F. Enquist, E.A. Gilmore, D.S. Gutzler, S. Harper, K. Holsman, E.B. Jewett, T.A. Kohler, and K. Miller, 2022: Ch. 14. North America. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1929–2042. https://doi.org/10.1017/9781009325844.016

72. Vogel, J., M.J. Kolian, A.S. Juliana, H. Hosterman, J. Peers, D. Krishland, and K. Carney, 2020: Past is prologue: A case study exploration of the role of climate indicators in adaptation in the United States. *Climate Services*, **20**, 100202. https://doi.org/10.1016/j.cliser.2020.100202

73. Ebi, K., C. Boyer, K. Bowen, H. Frumkin, and J. Hess, 2018: Monitoring and evaluation indicators for climate change-related health impacts, risks, adaptation, and resilience. *International Journal of Environmental Research and Public Health*, **15** (9), 1943. https://doi.org/10.3390/ijerph15091943

74. Kenney, M.A. and M.D. Gerst, 2021: Synthesis of indicators, datasets, and frameworks available to establish resilience and adaptation indicators: Case study of Chesapeake Bay region, USA. *Current Climate Change Reports*, **7** (2), 35–44. https://doi.org/10.1007/s40641-021-00170-6

75. EIA, 2023: Total Energy. U.S. Energy Information Administration, accessed April 13, 2023. https://www.eia.gov/totalenergy/data/browser/?tbl=t01.02#/?f=a

76. Colburn, L.L., M. Jepson, C. Weng, T. Seara, J. Weiss, and J.A. Hare, 2016: Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. *Marine Policy*, **74**, 323–333. https://doi.org/10.1016/j.marpol.2016.04.030

77. Ebi, K.L. and J.J. Hess, 2020: Health risks due to climate change: Inequity in causes and consequences. *Health Affairs*, **39** (12), 2056–2062. https://doi.org/10.1377/hlthaff.2020.01125

78. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

79. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

80. Reyes-García, V., Á. Fernández-Llamazares, M. Guèze, A. Garcés, M. Mallo, M. Vila-Gómez, and M. Vilaseca, 2016: Local indicators of climate change: The potential contribution of local knowledge to climate research. *WIREs Climate Change*, **7** (1), 109–124. https://doi.org/10.1002/wcc.374

81. Wyllie de Echeverria, V.R. and T.F. Thornton, 2019: Using traditional ecological knowledge to understand and adapt to climate and biodiversity change on the Pacific coast of North America. *Ambio*, **48** (12), 1447–1469. https://doi.org/10.1007/s13280-019-01218-6

82. FEMA, 2022: Community Resilience Indicator Analysis: Commonly Used Indicators from Peer-Reviewed Research: Updated for Research Published 2003–2021. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_2022-community-resilience-indicator-analysis.pdf

83. Cabell, J.F. and M. Oelofse, 2012: An indicator framework for assessing agroecosystem resilience. *Ecology and Society*, **17** (1). https://doi.org/10.5751/es-04666-170118

84. Brooks, N., 2014: Indicators for the Monitoring and Evaluation of Adaptation. IIED Briefing. International Institute for Environment and Development, 4 pp. https://www.iied.org/17273iied

85. Keenan, J.M. and K. Maxwell, 2021: Rethinking the design of resilience and adaptation indicators supporting coastal communities. *Journal of Environmental Planning and Management*, **65** (12), 2297–2317. https://doi.org/10.1080/09640568.2021.1971635

86. Brown, C., R.R. Shaker, and R. Das, 2018: A review of approaches for monitoring and evaluation of urban climate resilience initiatives. *Environment, Development and Sustainability*, **20** (1). https://doi.org/10.1007/s10668-016-9891-7

87. Blunden, J. and T. Boyer, 2021: State of the Climate in 2020. *Bulletin of the American Meteorological Society*, **102** (8). https://doi.org/10.1175/2021bamsstateoftheclimate.1

88. Reges, H.W., N. Doesken, J. Turner, N. Newman, A. Bergantino, and Z. Schwalbe, 2016: CoCoRaHS: The evolution and accomplishments of a volunteer rain gauge network. *Bulletin of the American Meteorological Society*, **97** (10), 1831–1846. https://doi.org/10.1175/bams-d-14-00213.1

89. Crimmins, T.M. and M.A. Crimmins, 2022: Large-scale citizen science programs can support ecological and climate change assessments. *Environmental Research Letters*, **17** (6), 065011. https://doi.org/10.1088/1748-9326/ac72b7

90. CDC, 2022: National Notifiable Diseases Surveillance System (NNDSS). Centers for Disease Control and Prevention. https://www.cdc.gov/nndss/index.html

91. Beauchamp, E., M. Hirons, K. Brown, and E.J. Milner-Gulland, 2020: Twenty priorities for future social-ecological research on climate resilience. *Environmental Research Letters*, **15** (10), 105006. https://doi.org/10.1088/1748-9326/abb157

Fifth National Climate Assessment: Appendix 5

# Glossary of Terms

# Appendix 5. Glossary of Terms

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# About the Glossary of Terms

Authors of the Fifth National Climate Assessment (NCA5) were encouraged to briefly define important terms within their chapters. Some terms, however, require more detailed or nuanced definitions. This Glossary was developed to help readers understand key terms and ensure consistency of usage across the report.

Most of the definitions presented here have been adapted from authoritative sources, including other US Global Change Research Program (USGCRP) reports, Intergovernmental Panel on Climate Change (IPCC) assessments, and academic and scientific societies and organizations (e.g., American Meteorological Society). These external sources are indicated with citations. Where definitions have been developed from multiple sources, the Fifth National Climate Assessment[1] is cited.

Where a term is used in a chapter in a manner that is inconsistent with the glossary definition, the intended definition is provided within the chapter text.

Terms and subterms (e.g., "Flash drought" as a subterm of "Drought") are bolded, and references to other terms defined in the glossary are underlined and hyperlinked. Related terms of particular importance are noted and linked at the end of the definition.

# Note on Glossary Development Process

Terms selected for inclusion in the Glossary of Terms are those that are used in multiple chapters of the Assessment and required a definition that went beyond what would be provided in a simple dictionary definition.

The editorial team followed a prioritized selection process for definitions. The team sought existing definitions from the following sources: the *Second State of the Carbon Cycle Report* (SOCCR2, 2018[2]); the *Climate Science Special Report* (Volume I of the Fourth National Climate Assessment [NCA4]; CSSR, 2017[3]); *Impacts, Risks, and Adaptation in the United States* (Volume II of NCA4; USGCRP, 2018[4]); *Impacts of Climate change on Human Health in the United States: A Scientific Assessment* (USGCRP, 2016[5]); and the Contributions of Working Groups I, II, and III to the IPCC Sixth Assessment Report (IPCC WGI, 2021[6] IPCC WGII, 2022[7] and IPCC WGIII, 2022[8]). If these sources did not offer adequate definitions, the editorial team searched for definitions from scientific and academic society glossaries, reports, and websites (e.g., American Meteorological Society, American Psychological Association, World Health Organization) and federal and state agency reports and websites. In the rare cases for which adequate definitions were not available from these sources, the editorial team collaborated with USGCRP leadership to develop definitions based on the text of the Assessment (or of NCA4) or the underlying Assessment literature.

As the editorial team examined sources, draft definitions were selected if they fit the proper context in which the term was used in the Assessment and were relatively succinct and understandable while also providing enough information for the reader to understand how the term was used. The team removed any policy-prescriptive terminology, assessment descriptions, or specific language referring to scenarios during editing, unless required to define the term.

The draft glossary was reviewed by Assessment author teams to ensure that all necessary terms were included and that the definitions were technically and scientifically accurate. The editorial team conducted an initial review for new term inclusion, as well as a science, technical, and stylistic edit of definitions, and these decisions were reviewed by the Assessment Director.

Finally, the Glossary of Terms was reviewed by the Federal Steering Committee prior to final copyediting and formatting.

# Glossary

**Note**: Underlined text indicates a term that is defined in the glossary.

| Term | Definition |
|---|---|
| **Acidification, ocean** | The process by which the pH measurement of ocean water moves toward more acidic levels due to the absorption of carbon dioxide, which interacts with ocean water to form carbonic acid, thereby lowering the pH. Increased acidity reduces the ability of plankton and shelled animals to form and maintain carbonate-containing body parts such as shells.[3] |
| **Adaptation** | **Climate adaptation:** In human systems, the process of adjustment to actual or expected climate and its effects to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects. Human intervention may facilitate adjustment to expected climate and its effects.[7] Related terms: Adaptive capacity, Maladaptation, Climate Resilience.<br><br>**Equitable adaptation:** Adaptation that intentionally incorporates recognitional, procedural, and distributional principles of equity in design, planning, and execution.[1,9]<br><br>**Incremental adaptation:** Adaptation that maintains the essence and integrity of a system or process at a given scale. In some cases, incremental adaptation can accrue to result in transformative adaptation. Incremental adaptations to change in climate are understood as extensions of actions and behaviors already known to reduce the losses or enhance the benefits of natural variations in extreme weather/climate events.[7]<br><br>**Transformative adaptation:** Adaptation that changes the fundamental attributes of a social–ecological system, often involving persistent, novel, and significant changes to institutions, behaviors, values, and/or technology in anticipation of climate change and its impacts.[1,8,10,11] |
| **Adaptive capacity** | The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.[7] |
| **Adaptive management** | A process of iteratively planning, implementing, and modifying strategies for managing resources in the face of uncertainty and change. Adaptive management involves adjusting management approaches in response to observations of their effect on, and changes in, the system brought on by resulting feedback effects and other variables.[7] |
| **Aeroallergens** | Various airborne substances, such as pollen or spores, that can cause an allergic response.[5] |
| **Aerosols (atmospheric)** | A suspension of airborne solid or liquid particles, with typical particle size in the range of a few nanometers to several tens of micrometers. Aerosols have both natural and human-caused sources. Overall, they tend to produce cooling by scattering incoming radiation and by affecting cloud cover, although some aerosols can cause warming directly by absorbing radiation and indirectly through their interactions with clouds.[2,6] Related term: Particulate matter. |
| **Afforestation** | The process of establishing trees on land that has lacked forest cover for a very long time or land that has never been forested.[2] Related terms: Deforestation, Reforestation. |
| **Agricultural intensification** | The process of increasing the use of capital, labor, and inputs (e.g., fertilizers, pesticides, machinery) relative to land area to increase agriculture productivity.[12] |
| **Agrivoltaics** | The use of land for both agriculture and solar photovoltaic energy generation. Agrivoltaics is also sometimes referred to as agrisolar, dual-use solar, or low-impact solar. Solar grazing is a variation where livestock graze in and around solar panels.[13] |

| Term | Definition |
|---|---|
| **Agroecology** | The science and practice of applying ecological concepts, principles, and knowledge to the study, design, and management of sustainable agricultural ecosystems. It includes the roles of human beings as a central organism by way of social and economic processes in farming systems. Agroecology examines the roles and interactions among all relevant biophysical, technical, and socioeconomic components of farming systems and their surrounding landscapes.[12] For NCA5, agroecology considers farming practices and management approaches that are developed through a systems science lens, taking into account local conditions and history. Agroecology might include subsistence and organic farming but might also include prudent use of resources through technological interventions (Ch. 11).[1] |
| **Agroforestry** | Collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economic interactions between the different components. Agroforestry can also be defined as a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production to increase social, economic, and environmental benefits for land users.[7] |
| **Air pollution** | Degradation of air quality with negative effects on human health or the natural or built environment due to the introduction, by natural processes or human activity, into the atmosphere of substances that have a direct (primary pollutants) or indirect (secondary pollutants) harmful effect.[6] Related terms: Ozone, Particulate matter, Carbon monoxide, Volatile organic compounds. |
| **Albedo** | The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo (highly reflective). Soil albedos range from high to low, and vegetation-covered surfaces and the ocean have a low albedo (low reflectivity). Earth's planetary albedo varies mainly through changes in cloudiness, snow, ice, leaf area, and land cover.[2] |
| **Altimetry** | A technique for measuring the height of Earth's surface with respect to the center of Earth's mass within a defined terrestrial reference frame.[3] |
| **Anthropogenic** | Caused or influenced by humans; human-induced.[2] |
| **Anthropogenic emissions** | Emissions of greenhouse gases (GHGs), precursors of GHGs, and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land-use and land-cover change, livestock production, fertilization, waste management, and industrial processes.[8] [This definition is in reference to human-caused emissions that drive changes in radiative forcing; for information on other emissions, see Air pollution.] Related terms: Air pollution, Emissions. |
| **Aquaculture** | The production of aquatic organisms under controlled conditions throughout part or all their life cycle.[14] Related term: Mariculture. |
| **Aquifer** | A layer of saturated geologic materials that could yield water to springs or wells.[15] |
| **Aridification** | Aridification is a transition of the climate and hydrology of a region toward drier conditions.[16] |
| **Assisted migration (ecological)** | Human-assisted movement of populations or species to a new location within the historical range, expansion of their historical range, or migration beyond locations accessible by natural dispersal to mitigate potential impacts of climate change.[17] |

| Term | Definition |
|---|---|
| **Atlantic meridional overturning circulation (AMOC)** | The main current system in the South and North Atlantic Oceans. AMOC transports warm upper-ocean water northward and cold deep-ocean water southward, as part of the global ocean circulation system.[3] Changes in the strength of AMOC can affect other components of the climate system.[6] |
| **Atmospheric river (AR)** | A long, narrow, and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in ARs is supplied by tropical and/or extratropical moisture sources. ARs frequently lead to heavy precipitation where they are forced upward, for example, by mountains or by ascent in a warm conveyor belt. Horizontal water vapor transport in the midlatitudes occurs primarily in ARs and is focused in the lower troposphere.[3] |
| **Attribution** | The process of evaluating the relative contributions of multiple causal factors to a change or event with an assessment of confidence.[8] |
| **Biochar** | Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Biochar is distinguished from charcoal by its application: biochar is used as a soil amendment with the intention to improve soil functions and to reduce greenhouse gas emissions from biomass that would otherwise decompose rapidly.[8] |
| **Biodiversity** | The variety of life, including the number of plant and animal species, other life forms, genetic types, habitats, and biomes in an ecosystem.[2] |
| **Bioenergy** | A form of renewable energy produced from plant and animal biomass.[2] |
| **Biofuel** | Fuel produced from plant or animal matter.[2] |
| **Biogeochemical cycles** | Fluxes or flows of chemical elements between Earth's different carbon reservoirs, such as from living to nonliving, from atmosphere to land or ocean, from plants to dead organic matter in soils, and from decomposition of organic matter into carbon-containing gases.[2] |
| **Biomass** | The mass of living organisms or the material derived from organisms.[2] |
| **Biosphere** | Parts of Earth's surface in which living organisms reside.[2] |
| **Black carbon** | Black carbon is a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths. Black carbon is the most effective form of particulate matter, by mass, at absorbing solar energy and is produced by incomplete combustion of carbon-based fuels.[18] |
| **Bleaching, coral** | Loss of coral pigmentation through the loss of intracellular symbiotic algae (known as zooxanthellae) and/or loss of their pigments.[6] |
| **Blocking (atmospheric)** | Associated with persistent, slow-moving high-pressure systems that obstruct the prevailing westerly winds in the middle and high latitudes and the normal eastward progress of extratropical transient storm systems. It is an important component of intra-seasonal climate variability in the extratropics and can cause long-lived weather conditions such as cold spells in winter and heatwaves in summer.[3] |
| **Blue carbon** | Carbon captured and stored by marine and coastal ecosystems such as mangroves, coastal wetlands, and seagrasses (Focus on Blue Carbon).[1] |
| **Boreal (zone)** | A biogeographical zone or region characterized by a northern type of fauna or flora. The zone has a definite winter with snow and a short, generally hot summer. It includes a large part of North America between the Arctic zone and about 40°N, extending to 35°N into the interior.[15] |

| Term | Definition |
|---|---|
| **Built environment** | The human-made or modified landscapes, structures, and infrastructure facilities that provide spaces for people to live, work, and recreate (Ch. 12).[1,19] |
| **Buyout** | A type of property acquisition program in which an entity, usually a government, purchases properties in high-risk areas with an intent to remove structures and create open space.[20] |
| **Carbon capture and storage (CCS)** | The process of capturing carbon dioxide and injecting it into geological formations underground or in the deep ocean for long-term storage.[2] Related term: Carbon sequestration. |
| **Carbon cycle** | The series of processes by which carbon compounds flow among reservoirs in the environment, such as the incorporation of carbon dioxide into living tissue by photosynthesis and its return to the atmosphere through respiration, the decay of dead organisms, and the burning of fossil fuels. In the carbon cycle, carbon flow or output from one reservoir transfers carbon to other reservoir(s).[2] |
| **Carbon dioxide ($CO_2$)** | A naturally occurring gas, as well as a by-product of burning fossil fuels from fossil carbon deposits, burning biomass, land-use changes, and industrial processes (e.g., cement production). $CO_2$ is the principal anthropogenic greenhouse gas that affects Earth's radiative balance. As the reference gas against which the radiative forcing of other greenhouse gases are measured, it has a global warming potential of 1.[2] Related terms: Global warming potential, carbon dioxide equivalent. |
| **Carbon dioxide equivalent ($CO_2$-eq)** | The amount of carbon dioxide emissions that would produce the same effect as another greenhouse gas (e.g., methane, nitrous oxide) on the radiative balance of Earth's climate system over a specified time horizon. $CO_2$-eq emissions are commonly used to compare emissions of different greenhouse gases but should not be taken to imply that these emissions have an equivalent effect across all measures of climate change.[2,8] Related terms: Carbon dioxide, Global warming potential. |
| **Carbon dioxide removal (CDR)** | A set of techniques that aim to remove and/or sequester carbon dioxide ($CO_2$) directly from the atmosphere by either increasing natural carbon sinks or using chemical engineering to remove the $CO_2$.[3] |
| **Carbon flux** | The direction and rate of transfer, or flows, of carbon between pools of carbon.[2] Related terms: Carbon cycle, Carbon sink, Carbon source. |
| **Carbon intensity / Emissions intensity** | A measure of the greenhouse gas or carbon dioxide emissions or removals per unit of activity or other defined variable, such as GDP, output energy use, or transport. For example, emissions intensity of energy generation sources is defined as the amount of greenhouse gases emitted per unit of energy produced (Ch. 30).[1,8] |
| **Carbon monoxide (CO)** | A colorless, odorless, poisonous gas produced by incomplete combustion. CO is oxidized to carbon dioxide and plays a part in local and regional air quality.[5,15] |
| **Carbon sequestration** | The storage of carbon through natural, deliberate, or technological processes in which carbon dioxide is diverted from emissions sources or removed from the atmosphere and stored biologically in the ocean and terrestrial environments (e.g., vegetation, soils, and sediment), underground, or in geological formations.[2] |
| **Carbon sink** | Any process, activity, or mechanism that removes carbon from the atmosphere. A carbon sink may also refer to a physical location, defined area, or geological or biological element of Earth's system (e.g., the ocean, a country, biomass) that stores acquired carbon from the atmosphere for a specified period of time.[1,2,3] Related terms: Carbon cycle, Carbon flux, Carbon source. |

| Term | Definition |
|---|---|
| **Carbon source** | Any process, activity, or mechanism that releases carbon into the atmosphere. A carbon source may also refer to a physical location, defined area, or geological or biological element (e.g., the ocean, a country, biomass) from which carbon is released to the atmosphere, either through natural or technological processes.[1,2,3] Related terms: Carbon cycle, Carbon flux, Carbon sink. |
| **Cascading impact** | Cascading impacts from extreme climate and weather occur when an extreme hazard (or cascading hazards) generates a sequence of secondary events (i.e., cascading events) in natural and human systems that result in physical, natural, social, or economic disruption (i.e., cascading effects), whereby the resulting impact is significantly larger than the initial impact. Cascading impacts are complex and multidimensional and are associated more with the magnitude of vulnerability than with the magnitude of the hazard.[7] Related term: Compound event. |
| **Climate** | Climate, in a narrow sense, is usually defined as the average weather or, more rigorously, as the statistical description in terms of the average and variability of defining factors over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate, in a wider sense, is the state, including a statistical description, of the climate system.[2] Related term: Weather. |
| **Climate change** | Changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changes in frequency and location of severe weather events, and changes to other features of the climate system.[2] Related term: Global warming. |
| **Climate feedback** | An interaction in which a perturbation in one climate quantity causes a change in a second, and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced. The initial perturbation can either be externally forced or arise as part of internal variability.[6] |
| **Climate model** | A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions, and feedback processes and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components, a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions; the extent to which physical, chemical, or biological processes are explicitly represented; or the level at which empirical parameterizations are involved. Climate models are applied as a research tool to study and simulate long-term climate projections (decadal or longer) and operationally used to create shorter climate predictions (seasonal, annual, interannual).[1,2] Related term: Earth system model. |
| **Climate projection** | The simulated response of the climate system to a scenario of future emissions or concentrations of greenhouse gases and aerosols, generally derived using climate models. Climate projections depend on the emissions, concentration, or radiative forcing scenario used, which, in turn, is based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.[2] Related terms: Climate, Climate model. |
| **Climate sensitivity** | The change in the surface temperature in response to a change in the atmospheric carbon dioxide concentration or other radiative forcing.[8] |
| **Climate services** | Climate services are scientifically based usable information and products that assist in decision-making and actions relevant to climate change risks, impacts, and responses. Climate services include appropriate engagement from users and providers, have effective access mechanisms, and respond to user needs.[1,6,21] |

| Term | Definition |
|---|---|
| **Climate-smart agriculture (CSA)** | An agricultural approach that helps guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate. CSA addresses three main objectives: sustainably increasing agricultural productivity and incomes, adapting and building resilience to climate change, and reducing and/or removing greenhouse gas emissions where possible.[7] |
| **Climate variability** | Deviations of climate variables from a given average state, including the occurrence of extremes, at all spatial and temporal scales beyond that of individual weather events. Variability may be intrinsic, due to fluctuations of processes internal to the climate system (i.e., internal variability), or extrinsic, due to variations in natural or anthropogenic external forcing (i.e., forced variability).[8] Related term: Natural variability, climate. |
| **Coastal zone** | The area extending from the ocean inland across the region directly influenced by marine processes.[22] Related term: Exclusive economic zone. |
| **Co-benefits** | The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as ancillary benefits.[2] |
| **Colonialism** | A form of domination in which at least one society exerts power to exploit one or more other societies in order to gain some set of goods it perceives as valuable to the fulfillment of its economic, social, and cultural development.[1,23]<br><br>**Settler Colonialism:** A type of domination in which a colonizing society seeks to obtain valuable goods by permanently inhabiting the territories that one or more other societies (e.g., Indigenous Peoples) already inhabit. Many settler colonial processes involve attempts by the colonizing society to erase the presence and history of the Indigenous Peoples.[1,23] |
| **Community health** | Community health encompasses approaches to promote health, well-being, and equity at the population level by addressing social, behavioral, environmental, economic, medical, and spiritual determinants of health.[24] Related terms: Health system / Healthcare system, Well-being. |
| **Community science / Citizen science** | Also known as participatory science, a participation by the public in advancing scientific knowledge by formulating research questions, collecting data, and interpreting results.[25] |
| **Compound event** | An event that consists of two or more extreme events occurring simultaneously or successively, combinations of extreme events with underlying conditions that amplify the impact of the events, or combinations of events that are not themselves extremes but lead to an extreme event or impact when combined. The contributing events can be of similar or different types.[3] |
| **Contaminant** | Any physical, chemical, biological, or radiological substance or matter found in any medium where it does not belong, particularly at concentrations that may pose a threat to human health or the environment.[5] |
| **Continental shelf** | The submerged margins of the continental plates, operationally defined as regions with water depths shallower than 656 feet (200 m).[2] |

| Term | Definition |
|---|---|
| **Coproduction (of knowledge)** | The integration of different knowledge systems and methodologies to systematically understand phenomena, systems, and processes.[26] |
| **Coupled Model Intercomparison Project (CMIP)** | A climate modeling activity from the World Climate Research Programme, which coordinates and archives climate model simulations based on shared model inputs by modeling groups from around the world. The CMIP Phase 3 (CMIP3) multimodel dataset includes projections using Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES). The CMIP Phase 5 (CMIP5) dataset includes projections using the Representative Concentration Pathways (RCPs). The CMIP Phase 6 (CMIP6) involves a suite of common model experiments as well as an ensemble of CMIP-endorsed Model Intercomparison Projects (MIPs).[8] Related terms: Representative Concentrated Pathways, Shared Socioeconomic Pathways. |
| **Cryosphere** | All regions on and beneath the surface of the Earth and ocean where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers, ice sheets, and frozen ground (e.g., permafrost).[2] |
| **Cultural burning** | The purposeful use of fire by a cultural group (e.g., family unit, Tribe, clan/moiety, society) for a variety of purposes and outcomes. Also called Indigenous prescribed burning.[27] Related terms: Prescribed fire, Wildfire. |
| **Debris flow** | Fast-moving landslides that generally occur during periods of intense rainfall or rapid snowmelt and usually start on hillsides or mountains. They can travel at speeds up to and exceeding 35 mph and can carry large items such as boulders, trees, and cars. Areas recently burned by a high-severity wildfire are especially susceptible to debris flows, including the areas downslope and outside of the burned area.[28] Related term: Landslide. |
| **Decarbonization** | Human actions to reduce carbon dioxide emissions from human activities.[7] |
| **Deforestation** | The process of removing or clearing trees from forested land with lasting conversion of that land to non-forest.[2] Related terms: Afforestation, Reforestation. |
| **Degree days, cooling (CDD) / Degree days, heating (HDD)** | A measure of the departure of the average daily temperature from a given standard: one degree day for each degree of departure above or below the standard for one day. Degree days can be accumulated over a "season" such that the total can be used as an index of the effect of past temperature on some quantity, such as plant growth, fuel consumption, or power output. CDDs are used to estimate energy requirements when the average daily temperature is higher than a given standard, while HDDs are used when the average daily temperature is lower than the standard. For example, if a standard/threshold of 65°F is used and a location has an average daily temperature of 75°F, then there were 10 CDDs for that day.[15,29] |
| **Deoxygenation (aquatic)** | See Hypoxia. |
| **Detection (climate)** | Detection (of change) is the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, less than 10%.[6] |
| **Disadvantaged community** | See Overburdened community. |

| Term | Definition |
|---|---|
| **Disaster risk management** | Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of current and future disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, prevention and protection, and response and recovery practices, with the explicit purpose of increasing human security, well-being, quality of life, and sustainable development.[7] |
| **Discount rate (economics)** | Discounting is a mathematical operation that uses a discount rate to make monetary (or other) amounts received or expended at different times (years) comparable across time. If the discount rate is positive, future values are given less weight than those today. The choice of discount rate(s) is debated as it is a judgment based on hidden and/or explicit values.[7] |
| **Discrimination** | The differential treatment of an individual or group of people on the basis of, for example, their race, color, national origin, religion, sex (including pregnancy and gender identity), age, marital and parental status, disability, sexual orientation, or genetic information.[30] |
| **Dissolved oxygen** | A measure of how much oxygen is dissolved in the water. Dissolved oxygen in surface water is used by all forms of aquatic life; therefore, this constituent typically is measured to assess the "health" of lakes and streams.[31] Related term: Hypoxia. |
| **Disturbance regime (ecological)** | The temporal and spatial characteristics of a disturbance agent and the impact of that agent on the landscape. More specifically, the cumulative effects of multiple disturbance events over space and time.[32] |
| **Domoic acid (poisoning)** | A harmful algal bloom toxin, domoic acid is a potent neurotoxin naturally produced by several species of the algal diatom genus *Pseudo-nitzschia*. Domoic acid usually transfers to higher-trophic-level animals via filter feeding bivalves or fish, exposing many vertebrate species including marine mammals, birds, and even humans. The clinical signs of acute domoic acid toxicity, well defined as amnesic shellfish poisoning, results in severe illness and sometimes death.[33] |
| **Downscaling** | A method that derives local- to regional-scale information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical methods are based on observations and develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the driving model remains an important limitation on quality of the downscaled information. The two methods can be combined, for example, applying empirical/statistical downscaling to the output of a regional climate model consisting of a dynamical downscaling of a global climate model.[6] Related term: Climate model. |

| Term | Definition |
|---|---|
| Drought | An exceptional period of water shortage for existing ecosystems and the human population (due to low rainfall, high temperature and/or wind).[34]<br><br>**Agricultural drought:** A period with abnormal soil moisture deficit that impinges on crop production, which results from a combined shortage of precipitation and excess evapotranspiration, generally during the growing season.[6,34,35]<br><br>**Ecological drought:** Depending on the affected biome, an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems.[34]<br><br>**Flash drought:** The rapid onset or intensification of drought. It is set in motion by lower-than-normal rates of precipitation, usually accompanied by abnormally high temperatures, winds, and incoming solar radiation.[6,34]<br><br>**Hydrological drought:** A period with large runoff and water deficits in rivers, lakes, and reservoirs.[6,34]<br><br>**Megadrought:** A very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.[6,34]<br><br>**Meteorological drought:** A period with an abnormal precipitation deficit.[6,34] |
| Earth system | Earth functions as a system of interdependent parts. These parts include the physical, chemical, and biological processes that all interact to shape our planet and the organisms on it.[36] Related term: Earth system model. |
| Earth system model (ESM) | A coupled atmosphere–ocean general circulation model in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric carbon dioxide or compatible emissions. Additional components (e.g., atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, and urban or crop models) may be included.[6] Related term: Climate model. |
| Eco-anxiety | Also known as climate anxiety, a chronic fear of environmental doom.[37] |
| Ecosystem | A functional unit consisting of living organisms, their nonliving environment, and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined. In some cases, ecosystem boundaries are relatively sharp, while in others they are diffuse, and they can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or they are influenced by the effects of human activities in their environment.[2] Related term: Ecosystem services. |
| Ecosystem-based adaptation | The use of ecosystem management activities to increase the resilience and reduce the vulnerability of people and ecosystems to climate change.[7] Related term: Adaptation, climate. |
| Ecosystem services | Ecological processes or functions that have monetary or nonmonetary value to individuals or society at large. These are frequently classified as supporting services such as productivity or biodiversity maintenance, provisioning services such as food or fiber, regulating services such as climate regulation or carbon sequestration, and cultural services such as tourism or spiritual and aesthetic appreciation.[7] Related term: Ecosystem. |

| Term | Definition |
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| **El Niño–Southern Oscillation (ENSO)** | A natural interaction between surface air pressure and surface water temperature in the tropical Pacific Ocean. ENSO has two phases: the warm oceanic phase, El Niño, accompanies high surface air pressure in the western Pacific, while the cold phase, La Niña, accompanies low surface air pressure in the western Pacific. Each phase generally lasts 6 to 18 months. ENSO events occur irregularly, about every 3 to 7 years. The extremes of this climate oscillation cause extreme events (such as floods and droughts) in many regions of the world.[2] |
| **Emissions** | The release of climate-altering gases and aerosols into the atmosphere from human and natural sources.[5] [This definition is in reference to greenhouse gas emissions. For information on other emissions, see Air pollution.] Related terms: Air pollution, Anthropogenic emissions. |
| **Emissions scenarios** | Quantitative illustrations of how the release of different amounts of climate-altering gases and aerosols into the atmosphere from human and natural sources will produce different future climate conditions. Scenarios are developed using a wide range of assumptions about population growth, economic and technological development, and other factors.[5] Related term: Scenario. |
| **Endemic (disease)** | The constant or usual presence of a disease or infectious agent within a geographic area or population.[5] |
| **Energy end use** | Energy used for services such as transportation, cooking, indoor thermal comfort, refrigeration, and illumination.[2] |
| **Energy supply** | The processes for extracting energy resources and converting them into more desirable and suitable forms of secondary energy and for delivering energy to places where demand exists.[2] |
| **Energy systems** | Comprises all components related to the production, conversion, delivery, and use of energy.[7] |
| **Ensemble (modeling)** | A collection of comparable datasets that reflect variations within the bounds of one or more sources of uncertainty and that, when averaged, can provide a more robust estimate of underlying model behavior. Ensemble techniques are used by the observational, reanalysis, and modeling communities.[6] |
| **Environmental injustice** | Environmental actions, behaviors, laws, and policies that have not been fair, that have limited meaningful involvement in environmental decision-making, or have unjustly allocated the risks and benefits of environmental action across communities, most often based on race, color, national origin, income, and gender identity, among others.[1,38] Related terms: Environmental justice, Justice, Just transition. |
| **Epidemiology** | The study of the distribution and determinants of health conditions, states, or events in specified populations.[5] |

| Term | Definition |
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| Equity | **Climate equity:** The principle of being fair and impartial and a basis for understanding how the impacts and responses to climate change, including costs and benefits, are distributed in and by society in more or less equal ways. Often aligned with ideas of equality, fairness, and justice and applied with respect to equity in the responsibility for, and distribution of, climate impacts and policies across society, generations, and gender, and in the sense of who participates and controls the processes of decision-making.[7]<br><br>**Health equity:** The attainment of the highest level of health for all people, where everyone has a fair and just opportunity to attain their optimal health regardless of race, ethnicity, disability, sexual orientation, gender identity, socioeconomic status, geography, preferred language, or other factors that affect access to care and health outcomes.[39]<br><br>**Social equity:** The consistent and systematic fair, just, and impartial treatment of all individuals—including individuals who belong to underserved communities and communities of color, people who belong to communities that may face discrimination, and people who live in rural areas—who have been systematically denied a full opportunity to participate in aspects of economic, social, and civic life.[40] |
| Evaporative demand | Evaporative demand quantifies the potential loss of water from the surface as driven by atmospheric factors including temperature, wind speed, humidity, and cloud cover. Periods of high evaporative demand are connected to droughts and increased fire danger.[41] |
| Evapotranspiration | The combined processes through which water is transferred to the atmosphere from open water and ice surfaces, bare soil, and vegetation that make up the Earth's surface.[8] Related term: Transpiration. |
| Exclusive economic zone | An area of the ocean, generally extending 200 nautical miles (230 miles) beyond a nation's territorial sea, within which a coastal nation has jurisdiction over both living and nonliving resources.[42] |
| Exposure | The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected by climate change.[8] Related terms: Hazard, Risk. |
| Extratropical cyclone | A large-scale (on the order of 600+ miles) storm in the middle or high latitudes having low central pressure and fronts with strong horizontal gradients in temperature and humidity. A major cause of extreme wind speeds and heavy precipitation, especially in wintertime.[3] |
| Extreme events | A weather event that is rare at a particular place and time of year, including, for example, heatwaves, cold waves, heavy rains, periods of drought and flooding, and severe storms. Definitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer than the 10% or 90% probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense.[2] |
| Extreme heat | Temperatures that are much hotter and/or humid than average. Because some places are hotter than others, this depends on what is considered average for a particular location at that time of year.[43] Related term: Heatwave. |
| Extreme precipitation | An extreme/heavy precipitation event is an event that is of very high magnitude with a very rare occurrence at a particular place. Types of extreme precipitation may vary depending on duration (hourly, daily, or multiday [e.g., 5 days]), although all of them qualitatively represent high magnitude.[6] |

| Term | Definition |
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| **Federally Recognized Tribes** | An American Indian or Alaska Native tribal entity that is recognized as having a government-to-government relationship with the United States—with the responsibilities, powers, limitations, and obligations attached to that designation—and is eligible for funding and services from the Bureau of Indian Affairs.[44] |
| **Fenceline community** | Communities located adjacent to hazardous industrial facilities, which are disproportionately BIPOC (Black, Indigenous, and People of Color) and low-wealth communities (Ch. 15).[1] Related terms: Frontline community, Overburdened community, Vulnerable community. |
| **Flood** | The overflowing of the normal confines of a stream or other water body or the accumulation of water over areas that are not normally submerged.[6]<br><br>**Flash flood:** A flood caused by heavy or excessive rainfall in a short period of time, generally less than six hours. Flash floods can occur within minutes or a few hours of excessive rainfall. They can also occur even if no rain has fallen, for instance, after a levee or dam has failed or after a sudden release of water by a debris or ice jam.[45]<br><br>**High tide flooding:** Occurs when sea level rise combines with local factors to push water levels above the normal high tide mark. Changes in prevailing winds, shifts in ocean currents, and strong tidal forces (which occur during full or new moons) can all cause high tide flooding, inundating streets and other infrastructure even on sunny days.[46] |
| **Food security** | When all people at all times have both physical and economic access to enough food for an active, healthy life.[2,47] Related terms: Food sovereignty, Subsistence. |
| **Food sovereignty** | The ability for nations, Tribes, and communities to feed their own people on their own terms.[48] Related term: Subsistence. |
| **Foodborne illness** | Illness or disease caused by foods or drinks contaminated with biological or chemical toxins or pathogens, including disease-causing microbes or toxic chemicals.[5] |
| **Forcing** | A change or impact to a factor that affects Earth's climate.[2] Related term: Radiative forcing. |
| **Fossil fuels** | Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas.[6] |
| **Fractionated (land ownership)** | As a result of the General Allotment Act of 1887, reservation land was divided up and allotted to individual Tribal members. After the death of the original allottee owner, title ownership was divided up among the heirs. As the land passed through each generation, the number of owners grew exponentially, resulting in the highly fractionated ownership of much Tribal land today.[49] |
| **Fragmentation (habitat, land)** | Occurs when a large, fairly continuous tract of vegetation is converted to other land cover or vegetation types such that only scattered fragments of the original type remain.[50] Related term: Land cover. |
| **Frontline community** | A community that includes people who are both highly exposed to climate risks (because of the places they live and the projected changes expected to occur in those places) and have fewer resources, capacity, social or economic safety nets, or political power to respond to those risks. Frontline communities are those that experience the "first and worst" consequences of climate change. These are often, but not limited to, communities of color and low-income communities.[1,9] Related terms: Overburdened community, Vulnerable community. |

| Term | Definition |
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| **Glacier** | A perennial mass of ice, and possibly firn and snow, originating on the land surface by accumulation and compaction of snow and showing evidence of past or present flow. A glacier typically gains mass by accumulation of snow and loses mass by ablation. Land ice masses of continental size are referred to as ice sheets.[6] Related term: Ice sheet. |
| **Global climate model (GCM)** | See Climate model. |
| **Global mean sea level (GMSL)** | The average of relative sea level or of sea surface height across the ocean.[3] |
| **Global warming** | The increase in global surface temperature relative to a baseline reference period, averaging over a period sufficient to remove interannual variations (e.g., 20 or 30 years). A common choice for the baseline is 1850–1900 (the earliest period of reliable observations with sufficient geographic coverage), with more modern baselines used depending on the application.[6] |
| **Global warming potential (GWP)** | An index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, carbon dioxide. The GWP thus represents the combined effect of the differing times these substances remain in the atmosphere and their effectiveness in causing radiative forcing.[6] Related term: Carbon dioxide equivalent. |
| **Governance** | The processes and structures that steer society and the multiplicity of actors who are involved. Institutional arrangements of governance comprise the sets of rules, norms, and shared practices that underlie decision-making.[2] |
| **Green infrastructure** | The strategically planned, interconnected set of natural and constructed ecological systems, green spaces, and other landscape features that can provide functions and services, including air and water purification, temperature management, floodwater management, and coastal defense, often with benefits for people and biodiversity. Green infrastructure includes planted and remnant native vegetation, soils, wetlands, parks, and green open spaces, as well as building and street-level design interventions that incorporate vegetation.[8] Related term: Nature-based solutions. |
| **Greenhouse gas (GHG)** | Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by Earth's surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor, carbon dioxide, nitrous oxide, methane, and ozone are the primary GHGs in Earth's atmosphere. Other GHGs include sulfur hexafluoride, hydrofluorocarbons, chlorofluorocarbons, and perfluorocarbons; several of these are also ozone-depleting (and are regulated under the Montreal Protocol).[6] Related term: Anthropogenic emissions. |
| **Greenhouse gas mitigation** | See Climate mitigation. |
| **Groundwater recharge** | The process by which external water is added to the zone of saturation of an aquifer, either directly into a geologic formation that traps the water or indirectly by way of another formation.[7] Related term: Aquifer. |
| **Growing degree days** | A heat index that relates the development of plants, insects, and disease organisms to environmental air temperature. Growing degree days are calculated by subtracting a base temperature from the daily average temperature, and growing degree day values less than zero are set to zero. The reference temperature (base temperature) below which development either slows or stops is species dependent. For example, the base temperature for cool-season plants (canning pea, spring wheat, etc.) is 40°F (5°C); for warm-season plants (sweet corn, green beans, etc.), 50°F (10°C); and for very-warm-season plants (cotton, okra, etc.), 60°F (15°C).[15] |

| Term | Definition |
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| **Harden (infrastructure)** | Hardening infrastructure means making infrastructure more resilient in the face of extreme events (such as hurricanes, tornadoes, and earthquakes) and other disasters, both natural and human-made.[1,51] Related terms: Built environment, Infrastructure. |
| **Hardiness zones (plants, agriculture)** | 10°F geographic bands based on the annual lowest winter temperature in a particular location, averaged over a period of years. They serve as a standard by which gardeners and growers can determine which plants are most likely to thrive at a location.[52,53] |
| **Harmful algal bloom (HAB)** | A sudden, rapid growth of algae in lakes, estuaries, and ocean waters caused by various factors including warmer surface waters, increased nutrient levels, or increased light levels. Some HABs may be toxic or harmful to humans and ecosystems.[2] |
| **Hazard** | The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.[7] Related terms: Impact, Risk. |
| **Health system / Healthcare system** | All organizations, people, and actions whose primary intent is to promote, restore, or maintain health. This may include infrastructure or systems of medical care services such as hospitals, clinics, home care, long-term care facilities, assisted living, physicians, health plans, and other community services.[1,54,55] |
| **Heatwave** | A period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months. Heatwaves and warm spells have various and, in some cases, overlapping definitions.[7] Related term: Marine heatwave. |
| **Homelessness** | See Unhoused and Unsheltered. |
| **Hydrocarbon** | A compound composed of hydrogen and carbon (e.g., petroleum products and fossil fuels).[2] |
| **Hypoxia (aquatic)** | Deficiency of oxygen in water bodies, defined as oxygen concentrations less than 2 milligrams per liter. Hypoxia can be a symptom of eutrophication (nutrient overloading). Deoxygenation (the process of removing oxygen) leads to hypoxia and the expansion of oxygen minimum zones.[2] Related term: Dissolved oxygen. |
| **Ice sheet** | An ice body originating on land that covers an area of continental size, generally defined as covering >19,000 square miles (>50,000 $km^2$) and that has formed over thousands of years through accumulation and compaction of snow.[6] Related term: Glacier. |
| **Impact (climate)** | The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health, and well-being; ecosystems and species; economic, social, and cultural assets; services (including ecosystem services); and infrastructure.[7] Related terms: Adaptation, Exposure, Hazard, Vulnerability, Risk. |
| **Indicator, climate** | An observation or calculation that allows scientists, analysts, decision-makers, and others to track environmental trends, understand key factors that influence the environment, and identify effects on ecosystems and society.[2] |

| Term | Definition |
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| **Indigenous communities / Indigenous Peoples** | Unless otherwise noted, this term is used in NCA5 to refer to culturally and politically self-determining groups whose right to self-determination in North America, Hawai'i, the US-Affiliated Pacific Islands, Puerto Rico, and the US Virgin Islands began before the establishment of the United States.[1] |
| **Indigenous Knowledges** | Bodies of dynamic and experiential knowledges gained over time by Indigenous Peoples, often associated with a specific place. Indigenous Knowledge includes observations, oral and written knowledge, innovations, practices, rituals, and beliefs; some Indigenous Knowledge is considered sacred and secret to a group or individuals. Indigenous Knowledge is inherently heterogeneous due to the cultural and geographic contexts from which it is derived. Also known as Native Science, Traditional Knowledges, Traditional Ecological Knowledges, or Indigenous Ways of Knowing.[1] |
| **Industrial era** | The multicentury period from the onset of large-scale industrial activity around 1750 to the present day. The reference period c. 1850–1900 is used to approximate preindustrial global average surface temperature.[6] Related term: Industrial Revolution. |
| **Industrial Revolution** | A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries, including the United States. The invention of the steam engine was an important trigger of this development. The Industrial Revolution marks the beginning of a strong increase in the use of fossil fuels, initially coal, and hence emissions of carbon dioxide.[6] Related terms: Industrial era. |
| **Inequity** | An unfair or unjust difference in the distribution, allocation, management, or use of a resource, benefit, or burden between groups of people.[1,56,57] Related terms: Equity, Injustice, Justice. |
| **Infrastructure** | The physical structures, services, and institutions (i.e., roads, electric utilities, legal systems) needed by a community, organization, or country.[5] Related terms: Green infrastructure, Built environment. |
| **Injustice** | Occurs when some benefit to which a person is entitled is denied without good reason or when some burden is imposed unduly.[58] Related terms: Equity, Inequity, Justice. |
| **Integrated assessment model (IAM)** | Models that integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments. One class of IAM used in respect to climate change mitigation may include representations of multiple sectors of the economy, such as energy, land use, and land-use change; interactions between sectors; the economy as a whole; associated greenhouse gas emissions and sinks; and reduced representations of the climate system. This class of model is used to assess linkages between economic, social and technological development, and the evolution of the climate system. Another class of IAM additionally includes representations of the costs associated with climate change impacts but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a cost–benefit framework and have been used to estimate the social cost of carbon.[6,8] |
| **Internal (climate) variability** | See Climate variability. |
| **Inundation (hydrology)** | The total water level that occurs on normally dry ground as a result of flooding. Along the coast, there are a few common sources of inundation, including abnormally high tides, storm surge, persistent onshore winds, and waves. In rivers and tidal estuaries, runoff from excessive rainfall can provide another source of inundation.[59] |
| **Invasive species** | A species that is not native to a specific location or nearby, lacks natural controls, and tends to rapidly increase in abundance, displacing native species. Invasive species may also damage the human economy or human health.[7] |

| Term | Definition |
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| **Irreversible (climate changes)** | Changes in components of the climate system that either cannot be reversed or can only be reversed on timescales much longer than the timescale of interest.[3] |
| **Just transition** | A set of principles, processes and practices that aim to ensure that no people, workers, places, sectors, countries, or regions are left behind in the transition from a high-carbon to a low-carbon economy. It stresses the need for targeted and proactive measures from governments, agencies, and authorities to ensure that any negative social, environmental, or economic impacts of economy-wide transitions are minimized, while benefits are maximized for those disproportionately affected. Key principles of just transitions include respect and dignity for vulnerable groups, fairness in energy access and use, social dialogue and democratic consultation with relevant stakeholders, the creation of decent jobs, social protection, and rights at work. Just transitions could include fairness in energy, land use, and climate planning and decision-making processes; economic diversification based on low-carbon investments; realistic training/retraining programs that lead to decent work; gender-specific policies that promote equitable outcomes; the fostering of international cooperation and coordinated multilateral actions; and the eradication of poverty. Lastly, just transitions may embody the redressing of past harms and perceived injustices.[8] Related term: Climate justice. |
| **Justice** | The moral or legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society.[7] Related term: Equity.<br><br>**Climate justice:** Justice that links development and human rights to achieve a human-centered approach to addressing climate change, safeguarding the rights of the most vulnerable people, and sharing the burdens and benefits of climate change and its impacts equitably and fairly.[7] Related term: Just transition.<br><br>**Distributional justice:** Allocating resources and opportunities, including access to information, so that no single group or set of individuals receives disproportionate benefits or burdens (Chs. 1, 20).[1]<br><br>**Environmental justice:** The just treatment and meaningful involvement of all people regardless of income, race, color, national origin, Tribal affiliation, or disability with respect to the development, implementation, and enforcement of environmental decision-making, laws, regulations, policies, and other related activities.[1,2,60] Related term: Environmental injustice.<br><br>**Procedural justice:** Ensuring that the people interested in and affected by outcomes of decision-making processes are fairly and meaningfully engaged and included (Chs. 1, 20).[1]<br><br>**Recognitional justice:** Acknowledging that certain people have borne disparate burdens related to current and historical social injustices and thus may have different needs (Chs. 1, 20).[1]<br><br>**Social justice:** Just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity, and support according to principles of justice and fairness.[7] |
| **La Niña** | See El Niño–Southern Oscillation. |
| **Land cover** | The physical characteristics of the land surface such as crops, trees, or concrete.[2] Related term: Land use. |
| **Land use** | Describes the human use of land. It represents the economic and cultural activities (e.g., agricultural, residential, industrial, mining, and recreational uses) that are practiced at a given place. Land use differs from land cover in that some uses are not always physically obvious.[61] Related term: Land cover. |
| **Landslide** | The movement of a mass of rock, debris, or earth down a slope.[62] Related term: Debris flow. |

| Term | Definition |
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| **Leakage** | Can refer to leakage of methane or other gases during drilling and storage and during transfers through pipelines. Leakage also can refer to the situation in which a carbon sequestration activity (e.g., tree planting or avoided deforestation) on one piece of land inadvertently, directly, or indirectly triggers an activity that in whole or in part counteracts the carbon effects of the initial activity.[2] |
| **Maladaptation (climate)** | Occurs when actions are taken that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.[7] |
| **Managed retreat** | See Planned relocation. |
| **Marginalized population / Marginalized community** | Community excluded from mainstream social, economic, educational, and/or cultural life. Examples of marginalized populations include, but are not limited to, groups excluded due to race, gender identity, sexual orientation, age, physical ability, language, and/or immigration status.[1,63] Related terms: Overburdened community, Underrepresented community. |
| **Mariculture** | Generally, aquaculture is the production of aquatic organisms under controlled conditions throughout part or all their life cycle. Mariculture (short for marine aquaculture) refers specifically to the culturing of oceanic species (as opposed to freshwater species).[14,64] Related term: Aquaculture. |
| **Marine heatwave** | A period during which water temperature is abnormally warm for the time of the year relative to historical temperatures, with that extreme warmth persisting for days to months. The phenomenon can manifest in any place in the ocean and at scales of up to thousands of kilometers.[8] |
| **Meteorological** | Referring to the atmosphere and its phenomena, particularly weather and weather forecasting.[5] |
| **Methane ($CH_4$)** | A greenhouse gas that is the major component of natural gas and is associated with all hydrocarbon fuels. Significant anthropogenic emissions of $CH_4$ also occur as a result of animal husbandry and paddy rice production. $CH_4$ is also produced naturally where organic matter decays under anaerobic conditions, such as in wetlands.[8] |
| **Microgrid** | A group of interconnected energy-consuming devices and equipment (e.g., homes, businesses, or industrial facilities) and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the utility grid. These microgrids generally operate while connected to the utility grid but can disconnect from the conventional utility grid and operate autonomously to meet anticipated or potential utility outages. A microgrid typically consists of a smart distribution network limited to a well-defined boundary, a load management system, distributed energy resources, and storage solutions. Distributed energy resources generate power in the form of solar panels, wind turbines, engine generators, or other power generation sources.[65] |
| **Migration (human)** | Movement of a person or a group of persons either across an international border or within a nation. It is a population movement encompassing any kind of movement of people, whatever its length, composition, and causes; it includes migration of refugees, displaced persons, economic migrants, and persons moving for other purposes, including family reunification.[7] |

| Term | Definition |
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| Mitigation | **Climate mitigation:** Measures to reduce the amount and rate of future climate change by reducing emissions of heat-trapping gases or removing carbon dioxide from the atmosphere.[2]<br><br>**Hazard mitigation:** Any sustained action taken to reduce or eliminate the long-term risk to human life and property from hazards.[66] |
| Monsoon | A shift in winds that often causes a very rainy season or a very dry season. Although monsoons are usually associated with parts of Asia, they can happen in many tropical and subtropical regions—including several locations in the United States.[67]<br><br>**North American Monsoon:** A regional-scale atmospheric circulation system with increases in summer precipitation over northwestern Mexico and the southwestern United States. The monsoonal characteristics of the region include a pronounced annual maximum of precipitation in boreal summer (June–July–August) accompanied by a surface low-pressure system and an upper-level anticyclone, although seasonal reversal of the surface winds is primarily limited to the northern Gulf of California.[6] |
| Morbidity | A disease or condition that reduces health and quality of life.[5] |
| Natural variability (climate) | Climatic fluctuations that occur without any human influence; that is, internal variability combined with the response to external natural factors such as volcanic eruptions, changes in solar activity, and, on longer timescales, orbital effects and plate tectonics.[6] Related term: Climate variability. |
| Nature-based solutions (NBSs) | Actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.[8] Related term: Green infrastructure. |
| Negative feedbacks | See Climate feedback. |
| Net-zero $CO_2$ emissions | Condition in which anthropogenic carbon dioxide ($CO_2$) emissions are balanced by anthropogenic $CO_2$ removals over a specified period.[6] |
| Net-zero greenhouse gas emissions | Condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period. The quantification of net-zero GHG emissions depends on the GHG emissions metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric.[6] |
| Nitrous oxide ($N_2O$) | The main anthropogenic source of $N_2O$, a greenhouse gas, is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, fossil fuel combustion, and chemical industrial processes. $N_2O$ is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests.[6] |
| North Atlantic Oscillation (NAO) | The leading mode of large-scale atmospheric variability in the North Atlantic basin characterized by alternating (see-saw) variations in sea level pressure or geopotential height between the Azores High in the subtropics and the Icelandic Low in the mid- to high latitudes, with some northward extension deep into the Arctic.[8] |
| Nutrients (ecological) | Chemicals such as nitrogen and phosphorous that plants and animals need to live and grow. At high concentrations, particularly in water, nutrients can become pollutants.[2,5] Related term: Harmful algal bloom. |

| Term | Definition |
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| **Overburdened community** | Population or geographic location in the United States that experiences disproportionate environmental and climatic harms and risks. This disproportionality can be a result of greater vulnerability to environmental hazards, lack of opportunity for public participation, or other factors. Increased vulnerability may be attributable to an accumulation of negative or lack of positive environmental, health, economic, or social conditions within these populations or places. The term describes situations where multiple factors, including both environmental and socioeconomic stressors, may act cumulatively to affect health and the environment and contribute to persistent environmental health disparities.[9,68] Related terms: Marginalized community, Underrepresented community, Underserved community. |
| **Ozone ($O_3$)** | The triatomic form of oxygen and a gaseous atmospheric constituent. In the troposphere, $O_3$ is created both naturally and by photochemical reactions involving gases resulting from human activities. Tropospheric $O_3$ acts as a greenhouse gas. $O_3$ in the upper atmosphere protects Earth from harmful levels of ultraviolet radiation from the sun. In near-surface air, $O_3$ is an air pollutant with harmful effects on human health.[2,6] |
| **Pacific Decadal Oscillation (PDO)** | A long-term ocean fluctuation of the Pacific Ocean. The PDO waxes and wanes approximately every 20 to 30 years. From ocean surface topography data, together with other ocean and atmospheric data, scientists can determine whether we are in a "cool" phase or a "warm" phase. The cool phase is characterized by a cool wedge of lower-than-normal sea surface heights and ocean temperatures in the eastern equatorial Pacific and a warm horseshoe pattern of higher-than-normal sea surface heights connecting the north, west and southern Pacific. In the warm, or "positive," phase, the west Pacific Ocean becomes cool, and the wedge in the east warms.[69] |
| **Paleoclimate** | Climate during periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available.[6] |
| **Paris Agreement** | An international climate agreement adopted in 2015 with the central aim to hold global temperature rise in this century to well below 2°C above preindustrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C. Under this agreement, all parties agreed to put forward emissions-reduction targets and to strengthen those efforts in the years ahead, as the agreement is assessed every five years. Each country's proposed mitigation target (the "intended nationally determined contribution") becomes an official "nationally determined contribution" when the country ratifies the agreement. Parties also agreed to adaptation efforts and finance mechanisms to support low greenhouse gas emissions and climate-resilient development.[3,70] |
| **Particulate matter (e.g., $PM_{2.5}$ and $PM_{10}$)** | A term for atmospheric aerosols often used when discussing surface air quality. Of greatest concern for health are particles of aerodynamic diameter less than or equal to 10 micrometers, usually designated as $PM_{10}$, and less than or equal to 2.5 micrometers, usually designated as $PM_{2.5}$.[8] Related term: Aerosols. |
| **Pathogen** | Microorganisms (e.g., bacteria) or viruses that cause disease.[2] |
| **Peatlands** | Peatlands are wetland ecosystems where soils are dominated by peat. In peatlands, net primary production exceeds organic matter decomposition as a result of waterlogged conditions, which leads to the accumulation of peat.[7] Related term: Soil organic matter. |
| **Permafrost** | Ground (soil or rock and included ice and organic material) that remains at or below 32°F (0°C) for at least two consecutive years.[7] |
| **pH** | A dimensionless measure of the acidity of water (or any solution) given by its concentration of hydrogen ions (H+). pH is measured on a logarithmic scale where pH = −log10(H+), where the concentration of hydrogen ions is measured in units of moles per liter. Thus, a pH decrease of 1 unit corresponds to a 10-fold increase in the concentration of H+, or acidity; a decrease of units corresponds to alkalinity; and 7 is a neutral reference point.[2] |

| Term | Definition |
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| **Phenology** | The pattern of seasonal life-cycle events in plants and animals, such as timing of blooming, hibernation, and migration.[2] |
| **Photosynthesis** | The process by which green plants, algae, and other organisms use sunlight to synthesize energy from carbon dioxide and water. Photosynthesis in plants generally involves the green pigment chlorophyll, consumes carbon dioxide and water, and generates oxygen as a by-product.[2] |
| **Photovoltaic (PV; solar)** | A system that converts sunlight directly into electricity using cells made of silicon or other conductive materials. When sunlight hits the cells, a chemical reaction occurs, resulting in the release of electricity.[71] Related term: Renewable energy. |
| **Phytoplankton** | Microscopic algae or other microorganisms that live in saltwater and freshwater environments.[2] |
| **Planned relocation** | In human systems, a form of mobility in response to direct climate impacts and/or indirect economic costs of estimated and projected climate impacts. Planned relocation, also referred to as managed retreat, is typically initiated, supervised, and/or implemented by public, private, and civic stakeholders and involves small communities and individual assets but may also involve large populations.[1,8] |
| **Positive feedbacks** | See Climate feedback. |
| **Post-traumatic stress disorder (PTSD)** | A mental health problem that can occur after war, assault, accident, natural disaster, or other trauma.[5] Related term: Trauma. |
| **Potential evapotranspiration (PET)** | The potential rate of water loss from wet soils and from plant surfaces, without any limits imposed by the water supply.[6] Related term: Evapotranspiration. |
| **Precursor emissions (biogeochemistry)** | As it refers to climate change, emissions of atmospheric compounds that are not greenhouse gases (GHGs) or aerosols but that have an effect on GHG or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates.[6] Related term: Air pollution. |
| **Premature death** | Death that occurs earlier than a specified age, often the average life expectancy at birth.[5] |
| **Prescribed fire** | The controlled application of fire by a team of fire experts under specified weather conditions to meet management objectives. Sometimes called a controlled burn or prescribed burn.[72,73] Related terms: Cultural burning, Wildfire. |
| **Primary productivity** | The synthesis of organic compounds by plants and microbes, on land or in the ocean, primarily by photosynthesis using light and carbon dioxide as sources of energy and carbon, respectively. It can also occur through chemosynthesis, using chemical energy, for example, in deep sea vents.[6] |
| **Proxy (data)** | Indirect measurement of climate aspects. Examples of proxy data are biological or physical records from ice cores, tree rings, and soil boreholes.[2] |

| Term | Definition |
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| **Radiative forcing** | The change in the net (downward minus upward) radiative flux (expressed in watts per square meter) at the tropopause or at the top of atmosphere due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide or in the output of the sun. Sometimes, internal drivers are still treated as forcings even though they result from the alteration in climate, for example, aerosol or greenhouse gas changes in paleoclimates. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once rapid adjustments are accounted for is the effective radiative forcing.[3] |
| **Redlining** | A practice in which lenders avoid providing services to individuals living in communities of color because of the race or national origin of the people who live in those communities. Redlining is now prohibited by the Fair Housing Act and the Equal Credit Opportunity Act.[74] |
| **Reforestation** | The process of establishing a new forest by planting or seeding trees in an area where trees have previously been removed.[2] Related terms: Afforestation, Deforestation. |
| **Relative humidity** | The ratio of actual water vapor pressure to that at saturation with respect to liquid water or ice at the same temperature.[6] |
| **Relative sea level** | The height of the sea surface, measured with respect to the height of the land at a particular location. Relative sea level changes in response to both changes in the height of the sea surface and changes in the height of the underlying land.[3,75] |
| **Remote sensing** | The process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance (typically from satellite or aircraft).[76] |
| **Remotely sensed data** | Data obtained via remote sensing. |
| **Renewable energy** | Any form of energy that is replenished by natural processes at a rate that equals or exceeds its rate of use.[8] |
| **Representative Concentration Pathways (RCPs)** | Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use and land cover. The word "representative" signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term "pathway" emphasizes that not only the long-term concentration levels are of interest but also the trajectory taken over time to reach that outcome. RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which integrated assessment models produced corresponding emissions scenarios. Extended concentration pathways describe extensions of the RCPs from 2100 to 2300 that were calculated using simple rules generated by stakeholder consultations and do not represent fully consistent scenarios.[6] Related terms: Radiative forcing, Scenario. |

| Term | Definition |
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| Resilience | The ability to prepare for threats and hazards, adapt to changing conditions, and withstand and recover rapidly from adverse conditions and disruptions.[1]<br><br>**Climate resilience:** The capacity of interconnected social, economic, and ecological systems to cope with a climate change event, trend, or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure. Climate resilience is a subset of resilience against climate-induced or climate-related impacts.[1,7] Related terms: Hazard, Risk, Vulnerability.<br><br>**Community resilience:** The ability of communities to withstand and recover and learn from past cumulative or compounding disasters to strengthen future response and recovery efforts. This can include, but is not limited to, physical and psychological health of the population, social and economic equity and well-being of the community, effective risk communication, integration of organizations (governmental and nongovernmental) in planning, response, and recovery.[77]<br><br>**Ecological resilience:** The capacity of natural systems subject to instability to absorb disturbances without shifting to a fundamentally different ecosystem domain.[1,78,79] |
| Respiration (biogeochemistry) | Metabolic pathways that break down complex molecules to release chemically stored energy for maintenance, growth, and reproduction, resulting in the release of waste products such as carbon dioxide, nitrous oxide, or methane.[2] |
| Riparian | Riparian zones, or areas, are lands that occur along the edges of rivers, streams, lakes, and other water bodies. Examples include streambanks, riverbanks, and floodplains.[80] |
| Risk | Threats to life, health, and safety, the environment, economic well-being, and other things of value. Risks are evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences).[2,5]<br><br>**Transition risk:** A risk associated with uncertain impacts, including financial and economic, that could result from a transition to a net-zero emissions economy.[81] Related term: Net-zero $CO_2$ emissions |
| Risk assessment | Studies that estimate the likelihood of specific sets of events occurring and their potential positive or negative consequences.[5] |
| Risk perception | The psychological and emotional factors that affect people's behavior and beliefs about potential negative hazards or consequences.[5] |
| Riverine | Includes all wetlands and deepwater habitats contained within a channel—except for wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens, or habitats with water containing ocean-derived salts of 0.5 parts per trillion or greater.[82] |
| Runoff | The flow of water over the surface or through the subsurface, which typically originates from the part of liquid precipitation and/or snow/ice melt that does not evaporate, transpire, or refreeze and returns to water bodies.[7] |
| Saltwater intrusion | Displacement of fresh surface water or groundwater by the advance of salt water due to its greater density. This usually occurs in coastal and estuarine areas due to decreasing land-based influence (e.g., from reduced runoff or groundwater recharge or from excessive water withdrawals from aquifers) or increasing marine influence (e.g., relative sea level rise).[7] |

| Term | Definition |
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| **Scenario** | A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts but are used to provide a view of the implications of developments and actions.[6] Related terms: Representative Concentration Pathways, Shared Socioeconomic Pathways. |
| **Sea level change** | See Sea level rise. |
| **Sea level rise** | Increase to the height of sea level, both globally and locally (relative sea level change) due to a change in ocean volume as a result of a change in the mass of water in the ocean (e.g., due to melt of glaciers and ice sheets), changes in ocean volume as a result of changes in ocean water density (e.g., expansion under warmer conditions), changes in the shape of the ocean basins, and changes in Earth's gravitational and rotational fields, as well as local subsidence or uplift of the land. Sea level change refers to sea level rise or sea level fall.[7] |
| **Sexual and gender minority (SGM)** | SGM populations include, but are not limited to, individuals who identify as lesbian, gay, bisexual, asexual, transgender, Two-Spirit, queer, and/or intersex (i.e., LGBTQI+). It is an umbrella term that refers to all people who are minorities based on their sexual orientation, gender identity and/or expression, and/or sex characteristics. LGBTQI+ people are SGM: lesbian, gay, and bisexual people are minorities based on their sexual orientation; transgender people are minorities based on their gender identity and/or expression; and intersex people are minorities based on their sex characteristics.[83,84] |
| **Shared Socioeconomic Pathways (SSPs)** | A basis for emissions and socioeconomic scenarios, an SSP is one of a collection of pathways that describe alternative futures of socioeconomic development in the absence of climate policy intervention. The combination of SSP-based socioeconomic scenarios and Representative Concentration Pathway–based climate projections can provide a useful integrative frame for climate impact and policy analysis.[3] Related term: Scenario. |
| **Sink** | Any process, activity, or mechanism that removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere.[8] Related terms: Carbon sequestration, Carbon sink. |
| **Snow water equivalent (SWE)** | The depth of liquid water that would result if a mass of snow melted completely.[3] Related term: Snowpack. |
| **Snowpack** | Snow that accumulates over winter and slowly melts to release water in spring and summer.[2] Related term: Snow water equivalent. |
| **Social determinants of health** | The conditions in the environments where people are born, live, learn, work, play, worship, and age that affect a wide range of health, functioning, and quality-of-life outcomes and risks. Social determinants of health can be grouped into five domains: economic stability, education access and quality, healthcare access and quality, neighborhood and built environment, and social and community context.[85] |
| **Socioeconomic** | Referring to a combination of social and economic factors, such as the education, income, and work status of individuals or communities.[5] |
| **Soil carbon** | The carbon content of soils, which can be from organic or inorganic sources. Related terms: Soil organic carbon, Soil organic matter.[1] |
| **Soil organic carbon** | The organic carbon content of soil organic matter. Soil organic matter and soil organic carbon in soil result from an imbalance between the supply of raw materials, such as plant, microbial, and animal parts and the decay of those materials by the soil microbial community and other biogeochemical processes.[2] Related term: Soil organic matter. |

| Term | Definition |
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| **Soil organic matter** | Organic material (e.g., carbon and other elements such as nitrogen) in soils. Soil organic matter results from an imbalance between the supply of raw materials such as plant, microbial, and animal parts and the decay of those materials by the soil microbial community. Soil organic matter forms the basis of life on Earth, enabling persistence and growth of the entire biosphere and can be considered in terms of its carbon content (e.g., soil organic carbon).[2] Related term: Soil organic carbon. |
| **Special Report on Emissions Scenarios (SRES)** | A set of emissions scenarios from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios, released in 2000, that describe a wide range of potential future socioeconomic conditions and resulting emissions.[5] Related term: Scenario. |
| **Stakeholder** | An individual or group that is directly or indirectly affected by or interested in the outcomes of decisions.[2] |
| **Statistical downscaling** | See Downscaling. |
| **Storm surge** | The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place.[2] |
| **Stressor** | A factor that negatively affects people and natural, managed, and socioeconomic systems. Multiple stressors can have compounded effects, such as when economic or market stress combines with drought to negatively impact farmers.[2] |
| **Subsidence** | Sinking of the ground because of underground material movement. Subsidence is most often caused by the removal of water, oil, natural gas, or mineral resources out of the ground by pumping, fracking, or mining activities. Subsidence can also be caused by natural events such as earthquakes, soil compaction, glacial isostatic adjustment, erosion, sinkhole formation, and the addition of water to fine soils deposited by wind.[86] Related term: Permafrost. |
| **Subsistence** | Taken broadly, refers to any human system that seeks to secure survival and flourish within particular ecosystems. In some legal and policy contexts, the term may be used more narrowly to refer to the provision of food that is a necessary part of a household's or a community's regular diet or to legal entitlements to harvesting rights in particular situations. In some contexts, subsistence means the harvest or use of naturally produced renewable resources for direct personal or family consumption, such as food, shelter, fuel, clothing, tools, or transportation, or for production of handicrafts for customary and traditional trade, barter, or sharing.[23] Related term: Food sovereignty. |
| **Surveillance (health)** | The collection, analysis, interpretation, and dissemination of health data.[5] Related term: Health system / Healthcare system. |
| **Sustainable development** | Development that meets the needs of the present without compromising the ability of future generations to meet their own needs and that balances social, economic, and environmental concerns.[7] |
| **Thermokarst** | Characteristic landforms that result from the thawing of ice-rich permafrost or the melting of massive ground ice.[2] |
| **Threshold** | The value of a parameter summarizing a system, or a process affecting a system, at which a qualitatively different system behavior emerges. Beyond this value, the system may not conform to statistical relationships that described it previously. For example, beyond a threshold level of ocean acidification, wide-scale collapse of coral ecosystems may occur.[2] Related term: Tipping point. |

| Term | Definition |
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| **Tipping point** | The point at which a change in the climate triggers a significant environmental event, which may be permanent, such as widespread bleaching of corals or the melting of very large ice sheets.[2] Related term: Threshold. |
| **Transpiration (biogeochemistry)** | The evaporation of water through plant leaves.[2] |
| **Trauma** | An adverse physical or psychological state caused by physical injury or mental stress.[5] |
| **Tundra** | A type of biome common to extreme northern and southern latitudes where tree growth is inhibited by low temperatures and short growing seasons.[2] |
| **Turbidity (hydrology)** | A measure of the level of particles such as sediment, plankton, or organic by-products in a body of water. As the turbidity of water increases, it becomes denser and less clear due to a higher concentration of these light-blocking particles.[87] |
| **Uncertainty (statistical)** | An expression of the degree to which a quantity or process is unknown. In statistics, a term used to describe the range of possible values around a best estimate, sometimes expressed in terms of probability or likelihood. Uncertainty about the future climate arises from the complexity of the climate system and the ability of models to represent it, as well as the inability to predict the decisions that society will make. There also is uncertainty about how climate change, in combination with other stressors, will affect people and natural systems.[2] |
| **Underrepresented community** | A community that has limited or no access to resources, is not well represented or meaningly involved in decision-making, or is otherwise disenfranchised. These communities may include people who are socioeconomically disadvantaged, people with limited English proficiency, geographically isolated or educationally disenfranchised people, people of color as well as ethnic and national-origin minorities, women and children, individuals with disabilities and others with access and functional needs, and seniors.[1,88] Related term: Underserved community. |
| **Under-resourced community** | See Underserved community. |
| **Underserved community** | A community that, due to continuous systemic discrimination, under- or disinvestments, and limited access to efficient, healthy, and affordable services and infrastructure, experiences disproportionate environmental and climatic harms and risks and lacks access to adequate resources to mitigate, respond to, and recover from impacts. Increased vulnerability may be attributable to harmful environmental, health, economic, or social conditions—or to a lack of support for positive conditions—within these populations or places. The term describes situations where disproportionate vulnerability is often due to discrimination based on geography; access to authority or representation in governance; or social identities, including race, ethnicity, gender, culture, economic status, or ability.[1,89,90] |
| **Unhoused** | US Code defines a person or persons experiencing homelessness (i.e., an unhoused person or people) as an individual or family who lack(s) a fixed, regular, and adequate nighttime residence, such as those living in emergency shelters, transitional housing, or places not meant for habitation.[91] Related term: Unsheltered. |
| **United Nations Framework Convention on Climate Change (UNFCCC)** | An international environmental treaty adopted on May 9, 1992, and ratified on March 21, 1994. The objective of the UNFCCC is to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.[2] |

| Term | Definition |
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| **Unsheltered** | An *unsheltered* unhoused person (i.e., a person experiencing homelessness) resides in a place not meant for human habitation, such as cars, parks, sidewalks, or abandoned buildings. A *sheltered* unhoused person resides in an emergency shelter or in transitional housing or supportive housing for unhoused persons who originally came from a place not meant for human habitation or emergency shelters.[92] Related term: Unhoused. |
| **Urban heat island effect** | The tendency for higher air temperatures to persist in urban areas because of heat absorbed and emitted by buildings and asphalt, tending to make cities warmer than the surrounding countryside.[2] |
| **Urban infrastructure** | See Infrastructure and Built environment. |
| **Vapor pressure deficit (VPD)** | The difference between how much moisture is in the air and the amount of moisture in the air at saturation (i.e., at 100% relative humidity) (Ch. 21 of NCA4).[4] Related term: Water vapor. |
| **Vector (disease)** | An organism, such as an insect, that transmits disease-causing microorganisms such as viruses or bacteria. Vector-borne diseases include, for example, malaria, Lyme disease, Zika, and chikungunya.[1,2] Related term: Zoonotic disease. |
| **Volatile organic compounds (VOCs)** | An important class of organic chemical air pollutants that evaporate readily at ambient air conditions. Other terms used to represent VOCs are hydrocarbons, reactive organic gases, and non-methane volatile organic compounds (NMVOCs). NMVOCs are major contributors—together with nitrogen oxides and carbon monoxide—to the formation of photochemical oxidants such as ozone.[6] Related terms: Precursor emissions, Air pollution. |
| **Vulnerability (climate)** | The degree to which physical, biological, and socioeconomic systems are susceptible to and unable to cope with adverse impacts of climate change.[2] |
| **Vulnerable community** | Communities of people who face disproportionate and unequal risks from projected and realized climate change impacts and who are least able to anticipate, cope with, and recover from these adverse impacts. Socioeconomic factors may include, but are not limited to, income, educational attainment, race and ethnicity, and age.[1,89] Related terms: Frontline community, Overburdened community. |
| **Water cycle** | The cycle in which water evaporates from the ocean and the land surface, is carried over the Earth in atmospheric circulation as water vapor, condenses to form clouds, precipitates over the ocean and land as rain or snow—which on land can be intercepted by trees and vegetation, potentially accumulating as snow or ice—provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, and ultimately flows into the oceans as rivers, polar glaciers, and ice sheets, from which it will eventually evaporate again. The various systems involved in the water cycle are usually referred to as hydrological systems.[6] |
| **Water quality** | Water quality can be thought of as a measure of the suitability of water for a particular use, such as for drinking water or supporting aquatic organisms and ecosystems, based on selected physical, chemical, and biological characteristics.[93,94] |
| **Water stress** | Water stress occurs when demand for water by people and ecosystems exceeds available supply.[2] |
| **Water vapor** | Water in the atmosphere in its vapor (gaseous) form. This gas absorbs and emits infrared radiation, which traps heat energy near Earth's surface.[95] |
| **Watershed** | An area of land that drains water to a particular stream, river, lake, bay, or ocean.[5] |

| Term | Definition |
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| **Weather** | The state of the atmosphere, mainly with respect to its effects on life and human activities. As distinguished from climate, weather consists of short-term (minutes to days) variations in the atmosphere. Popularly, weather is thought of in terms of temperature, humidity, precipitation, cloudiness, visibility, and wind.[15] Related term: Climate. |
| **Well-being (human)** | A state of existence that fulfills various human needs, including material living conditions and quality of life, as well as the ability to pursue one's goals, to thrive, and to feel satisfied with one's life.[7] |
| **Wetlands** | Soils that are inundated or saturated by water at a frequency and duration sufficient to support—and that do support under normal circumstances—a prevalence of vegetation typically adapted for life in saturated conditions. Tidal wetlands are influenced by ocean tides and may be saturated with salt water or fresh water. Terrestrial wetlands are nontidal and are saturated with fresh water.[2] |
| **Wildfire** | A wildland fire originating from an unplanned ignition, such as lightning, volcanos, unauthorized and accidental human-caused fires, and prescribed fires that are declared wildfires.[96] Related terms: Wildfire intensity, Wildfire severity. |
| **Wildfire intensity** | The product of the available heat of combustion per unit of ground and the rate of spread of the fire, interpreted as the heat released per unit of time for each unit length of fire edge.[96] Related terms: Wildfire, Wildfire severity. |
| **Wildfire severity** | The effect that wildfire has on vegetation, soils, buildings, watersheds, and similar physical features of the landscape.[97] Related terms: Wildfire, Wildfire intensity. |
| **Wildland–urban interface (WUI)** | The line, area, or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetation.[96] |
| **Woody encroachment (woody plants and shrubs)** | Refers to woody plants increasing in abundance or dominance in grasslands or other non-forested ecosystems.[2] |
| **Zoonotic disease** | A disease that can spread to people from other vertebrate animals. Examples of zoonotic diseases include Lyme disease, West Nile virus infection, Rocky Mountain spotted fever, and rabies.[5] Related term: Vector. |

# References


1. USGCRP, 2023: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023

2. SOCCR2, 2018: Appendix G: Glossary. In: *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*. Cavallaro, N., G. Shrestha, R. Birdsey, M.A. Mayes, R.J. Najjar, S.C. Reed, P. Romero-Lankao, and Z. Zhu, Eds. U.S. Global Change Research Program, Washington, DC, USA, 51–868. https://doi.org/10.7930/SOCCR2.2018.AppG

3. CSSR, 2017: Appendix E: Glossary. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. US Global Change Research Program, Washington, DC, 460–470. https://doi.org/10.7930/J0TM789P

4. USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/nca4.2018

5. USGCRP, 2016: Appendix 5: Glossary and acronyms. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 307–312. https://doi.org/10.7930/J02F7KCR

6. IPCC, 2021: Annex VII: Glossary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, S. Semenov, and A. Reisinger, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2215–2256. https://doi.org/10.1017/9781009157896.022

7. IPCC, 2022: Annex II: Glossary. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* Möller, V., R. van Diemen, J.B.R. Matthews, C. Méndez, S. Semenov, J.S. Fuglestvedt, and A. Reisinger, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2897–2930. https://doi.org/10.1017/9781009325844.029

8. IPCC, 2022: Annex I: Glossary. In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. van Diemen, R., J.B.R. Matthews, V. Möller, J.S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, A. Reisinger, and S. Semenov, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.020

9. Gauthier, T., L.A. Hamilton, A. Bennett, K. McCormick, A. Perrault, J. Smith, S. Hoverter, J. Li, and J. Grannis, 2020: Equitable Adaptation Legal and Policy Toolkit. Georgetown Climate Center, Washington, DC. https://www.georgetownclimate.org/adaptation/toolkits/equitable-adaptation-toolkit/financing-funding-tools-paying-for-equitable-adaptation.html

10. Fedele, G., C.I. Donatti, C.A. Harvey, L. Hannah, and D.G. Hole, 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, **101**, 116–125. https://doi.org/10.1016/j.envsci.2019.07.001

11. Termeer, C.J.A.M., A. Dewulf, and G.R. Biesbroek, 2017: Transformational change: Governance interventions for climate change adaptation from a continuous change perspective. *Journal of Environmental Planning and Management*, **60** (4), 558–576. https://doi.org/10.1080/09640568.2016.1168288

12. IPBES, n.d.: Glossary Tag: Agricultural Intensification. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, accessed June 28, 2023. https://www.ipbes.net/glossary-tag/agricultural-intensification#:~:text=Definition,seed%2C%20feed%20or%20cash

13. USDA, n.d.: Agrivoltaics: Coming Soon to a Farm Near You? U.S. Department of Agriculture, Northeast Climate Hub, accessed August 13, 2023. https://www.climatehubs.usda.gov/hubs/northeast/topic/agrivoltaics-coming-soon-farm-near-you

14. USDA, n.d.: Topics: Farming—Aquaculture. U.S. Department of Agriculture, accessed May 25, 2023. https://www.usda.gov/topics/farming/aquaculture

15. AMS, 2022: Glossary of Meteorology. American Meteorological Society, accessed August 14, 2023. https://www.ametsoc.org/index.cfm/ams/publications/glossary-of-meteorology/

16. USDA, n.d.: Megadrought and Aridification in the Southwest United States. U.S. Department of Agriculture, Southwest Climate Hub, accessed August 13, 2023. https://www.climatehubs.usda.gov/hubs/southwest/topic/megadrought-and-aridification-southwest-united-states

17. Handler, S., C. Pike, and B. St. Clair, 2018: Assisted Migration. U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. https://www.fs.usda.gov/ccrc/topics/assisted-migration

18. EPA, 2012: Report to Congress on Black Carbon. EPA-450/R-12-001. U.S. Environmental Protection Agency, Washington, DC. https://19january2017snapshot.epa.gov/www3/airquality/blackcarbon/2012report/fullreport.pdf

19. EPA, 2023: Basic Information About the Built Environment. U.S. Environmental Protection Agency, accessed May 23, 2023. https://www.epa.gov/smm/basic-information-about-built-environment

20. HUD, 2013: Disaster Recovery Buyout Program Design and Implementation Toolkit. U.S. Department of Housing and Urban Development and ICF. https://www.hudexchange.info/resource/2854/disaster-recovery-buyout-program-toolkit/

21. OSTP, 2023: A Federal Framework and Action Plan for Climate Services. White House Office of Science and Technology Policy. https://www.whitehouse.gov/wp-content/uploads/2023/03/ftac_report_03222023_508.pdf

22. CCSP, 2009: Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Environmental Protection Agency, Washington, DC, 320 pp. https://toolkit.climate.gov/reports/coastal-sensitivity-sea-level-rise-focus-mid-atlantic-region

23. NCA4 Resources, 2018: Indigenous Peoples Terminology for the Fourth National Climate Assessment. U.S. Global Change Research Program, Washington, DC. http://www7.nau.edu/itep/main/tcc/docs/resources/Indigenous%20Peoples%20Terminology%20for%20NCA4_final.pdf

24. AHA, 2023: Community Health & Well-Being: What is Community Health? American Hospital Association, Washington, DC, accessed May 23, 2023. https://www.aha.org/center/community-health-well-being

25. EPA, 2023: Participatory Science for Environmental Protection: What Is Participatory Science? U.S. Environmental Protection Agency, accessed August 13, 2023. https://www.epa.gov/participatory-science

26. NSF, 2020: Frequently Asked Questions (FAQs) for Navigating the New Arctic FY21 Solicitation (NSF 21-524). NSF 21-030. National Science Foundation, Alexandria, VA. https://www.nsf.gov/pubs/2021/nsf21030/nsf21030.pdf

27. Clark, S.A., A. Miller, and D.L. Hankins, 2021: Good Fire: Current Barriers to the Expansion of Cultural Burning and Prescribed Fire in California and Recommended Solutions. Karuk Tribe. https://karuktribeclimatechangeprojects.files.wordpress.com/2022/06/karuk-prescribed-fire-rpt_2022_v2-1.pdf

28. USGS, n.d.: Natural Hazards: What Is a Debris Flow? U.S. Department of the Interior, U.S. Geological Survey, accessed May 23, 2023. https://www.usgs.gov/faqs/what-debris-flow

29. USGCRP, 2023: USGCRP Indicators Platform. U.S. Global Change Research Program, accessed August 13, 2023. https://www.globalchange.gov/indicators/

30. DOI, n.d.: Equal Opportunity and Workplace Conduct: What Are Discrimination, Harassment, Harassing Conduct, and Retaliation? U.S. Department of the Interior, Washington, DC, accessed May 24, 2023. https://www.doi.gov/employees/anti-harassment/definitions

31. USGS, 2018: Water Science School: Dissolved Oxygen and Water. U.S. Department of the Interior, U.S. Geological Survey, Washington, DC, accessed August 13, 2023. https://www.usgs.gov/special-topics/water-science-school/science/dissolved-oxygen-and-water

32. Keane, R., 2017: Disturbance regimes and the historical range and variation in terrestrial ecosystems. In: *Reference Module in Life Sciences*. Elsevier. https://doi.org/10.1016/B978-0-12-809633-8.02397-9

33. NCCOS, 2012: Effects and Discovery of Chronic Domoic Acid Exposure on Gene Expression in the Vertebrate Central Nervous System. National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Silver Spring, MD, accessed May 24, 2023. https://coastalscience.noaa.gov/project/chronic-domoic-acid-exposure-gene-expression-central-nervous-system/

34. NOAA and NIDIS, 2023: Drought.gov: National Integrated Drought Information System. National Oceanic and Atmospheric Administration and National Integrated Drought Information System, Boulder, CO. https://www.drought.gov/

35. Crausbay, S.D., A.R. Ramirez, S.L. Carter, M.S. Cross, K.R. Hall, D.J. Bathke, J.L. Betancourt, S. Colt, A.E. Cravens, M.S. Dalton, J.B. Dunham, L.E. Hay, M.J. Hayes, J. McEvoy, C.A. McNutt, M.A. Moritz, K.H. Nislow, N. Raheem, and T. Sanford, 2017: Defining ecological drought for the twenty-first century. *Bulletin of the American Meteorological Society*, **98** (12), 2543–2550. https://doi.org/10.1175/bams-d-16-0292.1

36. Office of Science, n.d.: DOE Explains: Earth System and Climate Models. Department of Energy, Office of Science, Washington, DC, accessed May 24, 2023. https://www.energy.gov/science/doe-explainsearth-system-and-climate-models

37. Clayton, S., C. Manning, K. Krygsman, and M. Speiser, 2017: Mental Health and Our Changing Climate: Impacts, Implications, and Guidance. American Psychological Association and ecoAmerica, Washington, DC. https://www.apa.org/news/press/releases/2017/03/mental-health-climate.pdf

38. OEJ, 2004: Toolkit for Assessing Potential Allegations of Environmental Injustice. EPA 300-R-04-002. U.S. Environmental Protection Agency, Office of Environmental Justice, Washington, DC. https://www.epa.gov/sites/default/files/2015-02/documents/ej-toolkit.pdf

39. CMS, 2022: Health Equity. U.S. Department of Health and Human Services, Centers for Medicare and Medicaid Services, accessed August 13, 2023. https://www.cms.gov/pillar/health-equity

40. FEMA, 2022: FEMA's Equity Action Plan. U.S. Department of Homeland Security, Federal Emergency Management Agency, Washington, DC. https://www.fema.gov/emergency-managers/national-preparedness/equity

41. CNAP, 2022: Evaporative Demand. Abatzoglou, J., J. Kalansky, and D. McEvoy, Eds. California-Nevada Climate Applications Program, A NOAA RISA Team, San Diego, CA, 2 pp. https://cnap.ucsd.edu/wp-content/uploads/sites/430/2022/02/CNAPEvaporativeDemand_final.pdf

42. NOAA, n.d.: Ocean Exploration Facts: What Is the "EEZ"? National Oceanographic and Atmospheric Administration, accessed August 13, 2023. https://oceanexplorer.noaa.gov/facts/useez.html

43. CDC, 2023: Natural Disasters and Severe Weather: About Extreme Heat. Centers for Disease Control and Prevention, Washington, DC, accessed June 29, 2023. https://www.cdc.gov/disasters/extremeheat/heat_guide.html

44. BIA, 2020: What Is a Federally Recognized Tribe? U.S. Department of the Interior, Bureau of Indian Affairs, Washington, DC, accessed May 24, 2023. https://www.bia.gov/faqs/what-federally-recognized-tribe

45. NWS, 2023: Flood and Flash Flood Definitions. National Oceanic and Atmospheric Administration, National Weather Service, Morristown, TN, accessed May 24, 2023. https://www.weather.gov/mrx/flood_and_flash

46. NOS, 2023: Ocean Facts: What Is High Tide Flooding? National Oceanic and Atmospheric Administration, National Ocean Service, accessed May 24, 2023. https://oceanservice.noaa.gov/facts/high-tide-flooding.html

47. ERS, 2023: Food & Nutrition Assistance: Food Security in the U.S. U.S. Department of Agriculture, Economic Research Service, accessed May 25, 2023. https://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-u-s/

48. USDA, 2022: USDA Indigenous Food Sovereignty Initiative Fact Sheet. U.S. Department of Agriculture, 1 pp. https://www.usda.gov/sites/default/files/documents/ifsi-fact-sheet.pdf

49. BIA, n.d.: Land Buy-Back Program for Tribal Nations: Fractionation. U.S. Department of the Interior, Bureau of Indian Affairs, accessed May 24, 2023. https://www.doi.gov/buybackprogram/fractionation

50. Faaborg, J., M. Brittingham, T. Donovan, and J. Blake, 1993: Habitat fragmentation in the temperate zone: A perspective for managers. In: *Status and Management of Neotropical Migratory Birds: September 21–25, 1992, Estes Park, Colorado. Gen. Tech. Rep.* RM-229. Finch, D.M. and P.W. Stangel, Eds. U.S. Department of Agriculture, Forest Service, Fort Collins, CO, 331–338. https://www.fs.usda.gov/research/treesearch/22917

51. EOP, 2003: The National Strategy for the Physical Protection of Critical Infrastructures and Key Assets. Executive Office of the President, Washington, DC. https://www.dhs.gov/xlibrary/assets/Physical_Strategy.pdf

52. ARS, 2012: USDA Plant Hardiness Zone Map. U.S. Department of Agriculture, Agricultural Research Service, accessed May 25, 2023. https://planthardiness.ars.usda.gov/

53. Kaplan, K., 2012: USDA's New High-tech Guide to Green Thumb Glory. U.S. Department of Agriculture, Agricultural Research Service, accessed May 25, 2023. https://www.usda.gov/media/blog/2012/01/31/usdas-new-high-tech-guide-green-thumb-glory

54. Stedman, T.L., 2005: *Stedman's Medical Dictionary for the Health Professions and Nursing*, 5th ed. Jacobs, A.E., Ed. Lippincott Williams and Wilkins, Baltimore, MD. https://www.abebooks.com/9780781744263/Stedmans-Medical-Dictionary-Health-Professions-0781744261/plp

55. WHO, 2007: Everybody's Business—Strengthening Health Systems to Improve Health Outcomes: WHO's Framework for Action. World Health Organization, Geneva, Switzerland. https://apps.who.int/iris/handle/10665/43918

56. Meghani, S.H. and R.M. Gallagher, 2008: Disparity vs inequity: Toward reconceptualization of pain treatment disparities. *Pain Medicine*, **9** (5), 613–623. https://doi.org/10.1111/j.1526-4637.2007.00344.x

57. WHEJAC, 2021: Final Recommendations: Justice40 Climate and Economic Justice Screening Tool & Executive Order 12898 Revisions. White House Environmental Justice Advisory Council, Washington, DC, 92 pp. https://www.epa.gov/sites/default/files/2021-05/documents/whiteh2.pdf

58. NCPHSBBR, 1979: The Belmont Report: Ethical Principles and Guidelines for the Protection of Human Subjects of Research. U.S. Department of Health and Human Services, National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research, Washington, DC. https://www.hhs.gov/ohrp/regulations-and-policy/belmont-report/index.html

59. CO-OPS, n.d.: Coastal Inundation Dashboard: What is Inundation? National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services, accessed May 25, 2023. https://tidesandcurrents.noaa.gov/inundationdb_info.html

60. Executive Office of the President, 2023: Executive Order 14096: Revitalizing our nation's commitment to environmental justice for all. *Federal Register*, **88** (80), 25251–25261. https://www.federalregister.gov/documents/2023/04/26/2023-08955/revitalizing-our-nations-commitment-to-environmental-justice-for-all

61. EPA, 2023: Land Use: What Are the Trends in Land Use and Their Effects on Human Health and the Environment? U.S. Environmental Protection Agency, accessed August 13, 2023. https://www.epa.gov/report-environment/land-use

62. USGS, n.d.: Landslides Hazards Program: Landslides Glossary. U.S. Department of the Interior, U.S. Geological Survey, accessed May 25, 2023. https://www.usgs.gov/glossary/landslides-glossary

63. Sevelius, J.M., L. Gutierrez-Mock, S. Zamudio-Haas, B. McCree, A. Ngo, A. Jackson, C. Clynes, L. Venegas, A. Salinas, C. Herrera, E. Stein, D. Operario, and K. Gamarel, 2020: Research with marginalized communities: Challenges to continuity during the COVID-19 pandemic. *AIDS and Behavior*, **24** (7), 2009–2012. https://doi.org/10.1007/s10461-020-02920-3

64. NOAA, 2011: What Is Aquaculture? Learn More About this Increasingly Important Industry. National Oceanic and Atmospheric Administration, accessed May 25, 2023. https://www.noaa.gov/stories/what-is-aquaculture

65. FEMA, 2021: Hazard Mitigation Assistance Grant Funding for Microgrid Projects: Definition of a Microgrid. U.S. Department of Homeland Security, Federal Emergency Management Agency, Washington, DC, accessed May 25, 2023. https://www.fema.gov/fact-sheet/hazard-mitigation-assistance-grant-funding-microgrid-projects

66. 2002: Mitigation Planning. 44 C.F.R. § 201.2. https://www.ecfr.gov/current/title-44/chapter-I/subchapter-D/part-201#p-201.2(Hazard%20mitigation

67. NOAA, 2023: SciJinks: It's All About Weather! What is a Monsoon? National Oceanic and Atmospheric Administration, accessed May 25, 2023. https://scijinks.gov/what-is-a-monsoon/

68. EPA, 2023: EJ 2020 Glossary. U.S. Environmental Protection Agency, accessed May 25, 2023. https://www.epa.gov/environmentaljustice/ej-2020-glossary

69. JPL, 2023: El Niño/La Niña Watch & PDO. National Aeronautics and Space Administration, Jet Propulsion Laboratory, Pasadena, CA, accessed August 13, 2023. https://sealevel.jpl.nasa.gov/data/el-nino-la-nina-watch-and-pdo/pacific-decadal-oscillation-pdo/

70. UNFCCC, n.d.: The Paris Agreement: What Is the Paris Agreement? NDC Information. United Nations Framework Convention on Climate Change, accessed May 25, 2023. https://unfccc.int/process-and-meetings/the-paris-agreement

71. EPA, 2013: System of Registries: Terminology Services: Vocabulary Catalog. U.S. Environmental Protection Agency. https://sor.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details=&vocabName=Greening%20EPA%20Glossary

72. NPS, 2020: Wildland Fire: What Is a Prescribed Fire? U.S. Department of the Interior, National Park Service, accessed May 26, 2023. https://www.nps.gov/articles/what-is-a-prescribed-fire.htm

73. USFS, 2023: Managing the Land: Prescribed Fire. U.S. Department of Agriculture, Forest Service, accessed May 26, 2023. https://www.fs.usda.gov/managing-land/prescribed-fire

74. OPA, 2021: Justice Department announces new initiative to combat redlining. U.S. Department of Justice, Office of Public Affairs, Washington, DC, October 22, 2021. https://www.justice.gov/opa/pr/justice-department-announces-new-initiative-combat-redlining

75. EPA, 2023: Climate Change Indicators: Sea Level. U.S. Environmental Protection Agency, accessed August 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-sea-level

76. USGS, n.d.: What Is Remote Sensing and What Is It Used For? U.S. Department of the Interior, U.S. Geological Survey, Washington, DC, accessed August 14, 2023. https://www.usgs.gov/faqs/what-remote-sensing-and-what-it-used

77. OPR, 2018: Planning and Investing for a Resilient California: A Guidebook for State Agencies. California Office of Planning and Research, Sacramento, CA. https://opr.ca.gov/docs/20180313-Building_a_Resilient_CA.pdf

78. Davidson, J.L., C. Jacobson, A. Lyth, A. Dedekorkut-Howes, C.L. Baldwin, J.C. Ellison, N.J. Holbrook, M.J. Howes, S. Serrao-Neumann, L. Singh-Peterson, and T.F. Smith, 2016: Interrogating resilience: Toward a typology to improve its operationalization. *Ecology and Society*, **21** (2). https://doi.org/10.5751/ES-08450-210227

79. Meerow, S., J.P. Newell, and M. Stults, 2016: Defining urban resilience: A review. *Landscape and Urban Planning*, **147**, 38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011

80. NPS, 2022: Condition of Glen Canyon's Tributary Rivers and Associated Resources: Riparian Zones—It's All About the Water. U.S. Department of the Interior, National Park Service, accessed May 30, 2023. https://www.nps.gov/articles/000/nrca_glca_2021_riparian.htm

81. Climate-Related Market Risk Subcommittee, 2020: Managing Climate Risk in the U.S. Financial System. U.S. Commodity Futures Trading Commission, Market Risk Advisory Committee, Washington, DC, 165 pp. https://www.preventionweb.net/quick/50716

82. Federal Geographic Data Committee, 2013: Classification of Wetlands and Deepwater Habitats of the United States. FGDC-STD-004-2013. Second Edition. Wetlands Subcommittee, Federal Geographic Data Committee, and U.S. Fish and Wildlife Service, Washington, DC. https://www.fws.gov/wetlands/documents/Classification-of-Wetlands-and-Deepwater-Habitats-of-the-United-States-2013.pdf

83. NIH, 2023: About Sexual and Gender Minority Research Office (SGMRO). U.S. Department of Health and Human Services, National Institutes of Health, Bethesda, MD, accessed May 30, 2023. https://dpcpsi.nih.gov/sgmro

84. USAID, 2023: Integrating LGBTQI+ Considerations into Education Programming. U.S. Agency for International Development, Washington, DC. https://www.usaid.gov/sites/default/files/2023-01/Integrating_LGBTQI%2B_Considerations_into_Education_Programming_2023.pdf

85. OASH, n.d.: Healthy People 2030: Social Determinants of Health. U.S. Department of Health and Human Services, Office of Disease Prevention and Health Promotion, accessed August 14, 2023. https://health.gov/healthypeople/priority-areas/social-determinants-health

86. NOAA, n.d.: What is Subsidence? National Oceanographic and Atmospheric Administration, accessed August 13, 2023. https://oceanservice.noaa.gov/facts/subsidence.html#:~:text=Subsidence%20can%20also%20be%20caused,process%20known%20as%20loess%20deposits

87. USGS, 2018: Water Science School: Turbidity and Water. U.S. Department of the Interior, U.S. Geological Survey, Reston, VA, accessed June 1, 2023. https://www.usgs.gov/special-topics/water-science-school/science/turbidity-and-water

88. The White House, 2021: Executive Order On Advancing Racial Equity and Support for Underserved Communities Through the Federal Government. The White House, Washington, DC, January 20, 2021. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-advancing-racial-equity-and-support-for-underserved-communities-through-the-federal-government/

89. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. https://www.epa.gov/cira/social-vulnerability-report

90. FEMA, 2023: Glossary: Terms Frequently Used by FEMA. U.S. Department of Homeland Security, Federal Emergency Management Agency, Washington, DC, accessed June 1, 2023. https://www.fema.gov/about/glossary

91. 2002: Homeless Children. 34 C.F.R. § 300.19. https://www.ecfr.gov/current/title-34/subtitle-B/chapter-III/part-300/subpart-A/subject-group-ECFR0ec59c730ac278e/section-300.19

92. CPD, 2004: A Guide to Counting Unsheltered Homeless People. U.S. Department of Housing and Urban Development, Office of Community Planning and Development. https://www.hudexchange.info/sites/onecpd/assets/File/Guide-for-Counting-Unsheltered-Homeless-Persons.pdf

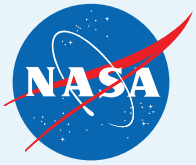
93. EPA, 2023: Basic Information on Water Quality Criteria. U.S. Environmental Protection Agency, accessed August 13, 2023. https://www.epa.gov/wqc/basic-information-water-quality-criteria

94. USGS, 2018: Water Science School: Water Quality Information by Topic. U.S. Department of the Interior, U.S. Geological Survey, Washington, DC, accessed August 13, 2023. https://www.usgs.gov/special-topics/water-science-school/science/water-quality-information-topic

95. NOAA, n.d.: Climate Data Primer: How Do We Observe Today's Climate? Air—Atmospheric Climate Variables. National Oceanic and Atmospheric Administration, accessed June 1, 2023. https://www.climate.gov/maps-data/climate-data-primer/how-do-we-observe-todays-climate/air-atmospheric-climate-variables

96. NWCG, 2019: Federal Wildland Fire Policy Terms and Definitions. FMB Memorandum 19-004. National Wildfire Coordinating Group, Fire Managment Board, Washington, DC. https://www.nwcg.gov/sites/default/files/docs/eb-fmb-m-19-004a.pdf

97. Graham, R.T., S. McCaffrey, and T.B. Jain, 2004: Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity. Gen. Tech. Rep. RMRS-GTR-120. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 43 pp. https://www.fs.usda.gov/rm/pubs/rmrs_gtr120.pdf



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